MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY

Vol. 105 No. 2

1945 APRIL 13

ANNUAL GENERAL MEETING

Professor E. A. Milne, President, in the Chair

The Minutes of the preceding Annual General Meeting were read and confirmed.

The following candidates were proposed for election as Fellows of the Society, the names of the proposers from personal knowledge being appended:—

Frank J. Acfield, 61 Great Lime Road, Forest Hall, Northumberland (proposed by W. B. Housman);

Desmond Egan Andrew, A.R.Met.Soc., 29 Liverpool Road, Chester (proposed by D. P. Bayley);

Roy Henry Garstang, Gonville and Caius College, Cambridge (proposed by H. A. Brück);

Alfred Llewelyn Middleton, B.A., 42B Fellows Road, London, N.W. 3 (proposed by E. L. Hawke);

Barrie Were Ashley Ricketson, Chestnut Cottage, Broadway, Worcestershire (proposed by H. H. Plaskett); and

Henry Wildey, 14 Savernake Road, Hampstead, London, N.W. 3 (proposed by P. M. Ryves).

The election by the Council of the following Fellows was duly confirmed:—

Josef C. Bartosik, D.S.C., Polish Naval H.Q., 51 New Cavendish Street, London, W. 1;

John L. Hull, 15 Mt. Stuart Road, North Hobart, Tasmania;

William Hugh Marshall, B.Sc., 83 Irvine Road, Kilmarnock, Ayrshire;

Arthur Herbert Prickett, H.M. Coastguard, Cromarty, Ross-shire;

Raymond Frederick Saxe, B.Sc., 15 Rivington Avenue, Woodford Green, Essex; and

Ernest Thomas Walcroft, M.I.Mar.E., 99 Brownlow Road, Horwich, near Bolton, Lancashire.

The Address on the award of the Gold Medal was delivered by the President (see p. 138), after which the Gold Medal was handed to Baron K. G. Lagerfelt, First Secretary at the Swedish Legation, for transmission to Professor Bengt Edlén, to whom it had been awarded for his identification of the origin of the principal lines in the coronal spectrum.

The President then delivered his Address on "The Natural Philosophy of Stellar Structure" (see p. 146).

After the delivery of the President's Address, visitors were requested to withdraw and the Society proceeded to the formal business of the Meeting.

The Report of the Auditors was read (see p. 52).

The Secretary read the paragraph on *Finance* from the Annual Report of Council and the Treasurer spoke on one or two special items appearing in the accounts for the year 1944.

A vote of thanks to the Auditors of the Treasurer's Accounts for 1944 was proposed and carried unanimously.

The Secretary read extracts from the Annual Report of the Council.

It was proposed and carried that the Report of the Council be received and adopted, and that it be printed and circulated in the usual manner, together with the Report of the Auditors and the President's Addresses.

The President having appointed the Scrutineers, the Society proceeded to the ballot for Officers and Council for the ensuing year. The names of those elected are given on p. 163.

The thanks of the Society were given to the retiring President (Professor Milne) and other retiring members of Council.

The thanks of the Meeting were given to the Scrutineers of the ballot.

The Meeting then adjourned.

REPORT OF THE COUNCIL TO THE HUNDRED AND TWENTY-FIFTH ANNUAL GENERAL MEETING OF THE SOCIETY

1. *General.*—The Society has suffered a grievous loss by the death, at an early age, of its Foreign Secretary, Sir Arthur Eddington, O.M., F.R.S. He will be sadly missed both at Council and Ordinary Meetings. (The text of the motion of condolence sent by Council to Miss Eddington was read to the Society by the President at the Ordinary Meeting on March 9 and is printed on p. 1.)

The various activities of the Society have been carried on throughout the year in accordance with the established war-time arrangements, apart from the cancellation of the July meeting. In many ways Astronomy has been the science most severely affected by the war, since the majority of astronomers have been engaged on work with little or no connection with their subject. With the prospect of their early return to astronomical work, the Society can look forward to a heightening of interest in its activities and to a gradual return to normal conditions; it can look backwards with some satisfaction to the way in which its principal functions have been maintained throughout the war years.

In common with the other scientific societies in Burlington House, the Society was represented on a deputation, headed by the Royal Society, which waited on the Lord President of the Council and the Chancellor of the Exchequer for the purpose of presenting the urgent need for a suitable central home for science. The sympathetic reception accorded to the strong case put forward has encouraged the Societies to proceed with the formulation of a quantitative estimate of the accommodation required, so that this may be considered in detail by H.M. Government.

This Report of Council follows the standardised form. It is customary to include with the Report, Obituary Notices of deceased Fellows and Associates, Proceedings of Observatories and Notes on the Progress of Astronomy; the Proceedings of Observatories have been restricted to those of active observatories, but include reports for both 1943 and 1944.

2. *Bye-laws.*—At the Annual General Meeting, on April 14, the Society adopted an amended form of Bye-law 26A, which had been proposed by Council. The object of the amendment was to remove the possibility of misinterpretation of the phrase "end of the emergency period (*i.e.* the end of the year in which peace is declared)"; this is the more important in view of the extension of the provisions of the Bye-law to Fellows who, although not necessarily on active service, are unable to continue to pay their annual contributions owing to war conditions. Council accordingly recommended that it should be given discretion to act according to the varying conditions that might prevail, if necessary on a geographical basis; this has been accomplished by the substitution of the words "Council decides otherwise" for the above phrase.

No other amendments have been made to the Bye-laws.

3. *Membership.*—The Council record with regret the death of twenty-one Fellows;

their deaths occurred in 1944 except where an earlier year is indicated. Obituary Notices are given on pp. 65–104.

Stanley Philip Benge (1943)
Mary Adela Blagg
*John Brittain (1943)
Arthur W. Clayden
*Alexander Eugen Conrady
*Josiah Owen Corrie (1924)
*Arthur Stanley Eddington
Ralph Howard Fowler
Philip Fox
Murray Geddes
Henry Ernest Green
Samuel Morris Green
*Thomas Herbert Le Sbirel Hony
Donald William Horner
Thomas A. Lumsden
*Stanley Maxwell
*Hugh Frank Newall
Jacobus Cornelius Reyneke (1943)
William Smalley
Charles John Veale
Leslie Woolven

* Life Fellow.

A table giving detailed statistics of the membership of the Society on 1945 January 1 is given on p. 53.

4. *Finance.*—The Annual Accounts from 1944 January 1 to December 31 have been presented in much the same form as last year; they have been audited by the professional auditors, Messrs. Sharp, Parsons & Co., and certified correct.

The Cash Account shows a cash balance at the Westminster Bank, Post Office Savings Bank, and in the London Savings Bank on 1944 December 31 of £5451, 4s. compared with £4758, 7s. 3d. on 1944 January 1.

The Revenue Account shows a net surplus of £169, 4s. 1d., after making the annual reserve of £40 for repairs, £150 for the Staff Pension Fund, and a new reserve of £25 for the replacement of photographic slides and prints. In the Balance Sheet there has been an item of £170, 7s. 8d. brought forward from previous years on the Franklin-Adams Charts, which represents the margin between the cost of publication and sales. The Council has agreed to transfer this item to the fund for the replacement of photographic slides and prints, the stock of which is now practically exhausted.

It will be noticed that in the Balance Sheet the Goodridge Bequest and the Grove-Hills Special Fund have been included in the General Funds of the Society as there seems to be no purpose served now by keeping them separate.

The total of the Suspense Account and unpaid Contributions and Admission Fees amounts to £963, 18s.; no credit for this sum has been taken in the Annual Accounts.

During the year a revised Staff Pension Scheme has been inaugurated with the approval of the Inland Revenue Authorities; the Scheme was prepared by the Equitable Life Assurance Society with whom insurances for the staff had originally been effected, and it was adopted by the Council on 1944 December 8. It was found that the Scheme started in 1922 had not been passed by the Inland Revenue, and the revised Scheme was not therefore officially recognised by them until 1945 February 2, although they had previously approved the draft provisions of the Scheme.

5. *Meetings during* 1944.—The Annual General Meeting was held in April and there were five Ordinary Meetings in March, May, June, September and October. The July meeting was cancelled owing to possible danger from Flying Bombs. As in previous war-time years, meetings began at $16^h\ 30^m$ and were timed to end at 18^h. The verage attendance of Fellows (as shown by the signatures in the Attendance Book, nd excluding visitors) was 55 as compared with 52 in 1943.

The George Darwin Lecture was delivered at the October meeting, and the remaining four meetings were devoted to the reading of original papers communicated to the Society.

6. *Geophysical Discussions.*—A Geophysical Discussion was held in December, the subject being "Astronomical and Geophysical Periodicities".

7. *George Darwin Lecture.*—Professor Joseph Proudman, M.A., D.Sc., F.R.S., gave the George Darwin Lecture at the Ordinary Meeting on October 13, taking as his subject "The Tides of the Atlantic Ocean".

8. *Awards.*—The Council awarded the Gold Medal of the Society to Professor Otto Struve, Ph.D., Assoc.R.A.S., for his work on the observation and interpretation of the spectra of stars and nebulæ. The President's address on the award is printed in *M.N.*, **104**, 112.

9. *Publications.*—During 1944 the Society published Volume **104** of *Monthly Notices*; no *Geophysical Supplement* was issued.

As in previous war-time years, the volume of *Monthly Notices* has been restricted to six numbers only, not associated with particular monthly meetings. The total number of pages in Vol. **104** is 340, as compared with 354 in Vol. **103** and the pre-war average of about 800; when account is taken of the increased type area and smaller type, it will be seen that the total amount of matter printed is over half the average.

During the year the Society has received a small increase in the allocation of paper, specifically to increase circulation; the cut made in the number of copies printed has been partially restored and it is further hoped to increase the number of reprints allowed to authors. It has just been possible to keep within permitted paper supplies without having to decline papers on this account alone; conciseness is still, however, a necessity.

Council has decided to revive *Occasional Notes* in order to make available to Fellows translations of some of the early books on astronomy belonging to the Society. The first translation to be published will be of the Preface and Book I of *De Revolutionibus Orbium Coelestium* by Copernicus.

10. *Exchange of Publications.*—The Society is again indebted to the American Committee for the Continued Distribution of Astronomical Literature for copies of publications it would not otherwise have received, for its regular *Bulletins* and for distributing copies of *Monthly Astronomical News Letter.* During the year advantage has also been taken of the microfilm service organised by the Committee; the titles of papers available in this form are published, by courtesy of the Editors, in *The Observatory.*

The distribution of *Monthly Notices* to countries with which normal communication is impracticable has been greatly assisted by the Astronomer Royal and by the British Council. The liberation of Italy, France and Belgium has not so far made possible full restoration of exchange facilities with institutions in those countries, but one or two complete sets of war-time publications are being sent to the principal Observatories and Astronomical Institutions as channels become available. While it is hoped shortly to resume the despatch of current publications to these countries, it will not immediately be practicable to make up war-time gaps for all the Institutions on the exchange list.

The list of *Exchanges* has again been omitted from the Report.

11. *The Library.*—The use made of the Library continues to increase and, in 1944, 395 books were borrowed by 90 different borrowers, as compared with the figures of 349 books and 78 borrowers in 1938.

Three lists of *Additions to the Library* (other than by exchange) were issued during 1944; from these lists it will be seen that again the Society has been presented with and has purchased several old books to supplement its collection of early astronomical literature. The thanks of the Society are due to Mr. W. H. Owston for his generosity in presenting £21, 17s. 6d. for the purchase of three such books. The Society gratefully accepted the present by the widow of the late Hon. Lionel Guest of one hundred

scientific books either for the Society's own use or for disposal, after the war, to other libraries requiring them.

The problem of the restocking of destroyed or damaged astronomical libraries has already been considered by Council, and a collection of duplicate books is being made for this purpose. In response to an appeal from the Inter-Allied Book Centre for the collaboration of the Society in providing books and periodicals of real scientific value for the war-damaged libraries of the allied countries, an appeal has been addressed to Fellows to send, in the first place, titles of such books as they can spare to the Society. It is generally felt that the Society will best be able to recommend the most suitable Institutions for the receipt of astronomical books.

The Society has presented two books to the collection being made by representative individuals, institutions and societies for presentation to the Cape Town Library as a tribute to Field-Marshal Smuts and his Springboks.

The more rare and valuable books are still at Oxford; it has again not been possible to do any binding.

12. *The Society's Office and Staff.*—No changes have taken place during the year.

13. *The Society's Property and Instruments.*—The Society's more valuable property continues to be stored either in the strong room at Burlington House or at the University Observatory, Oxford.

Some essential repairs and improvements were carried out during the year, mainly to the central heating system.

Various instruments have been lent and returned during the year. Several of the Society's instruments continue to be housed at the Headley Observatory, of which the Society, jointly with the British Astronomical Association, temporarily hold the lease; although considerable damage was caused to the Observatory buildings by a Flying Bomb, the instruments are undamaged. Temporary repairs have been made to the buildings which are now weatherproof. A new list of instruments is in preparation and no list is included in the Report.

No new slides or celestial photographs have been added to the Society's collection during the year.

14. "*The Observatory*".—In accordance with the agreement of 1941, Fellows have received the six 1944 issues of the magazine. The Editors have co-operated with the Council in the insertion of notices and information of particular interest to Fellows. Fellows are reminded that information about the Society's activities (for instance, details of papers available in microfilm form) will often be published solely in the pages of *The Observatory*.

To save the heavy expense of separate distribution to Fellows, it has been agreed to circulate the magazine with *Monthly Notices* even though this may involve delay.

15. *The British Astronomical Association.*—During 1944 the British Astronomical Association continued to hold both Ordinary and Council meetings on the Society's premises. The Association's library is open to members from 13^h to 16^h on Wednesdays.

16. *The London Mathematical Society.*—Meetings of the London Mathematical Society were held on three occasions in the Society's rooms.

17. *Lectures for the Forces.*—The success of the lectures on astronomy for members of the British and Allied Forces given in the Society's rooms in the winter months of 1943–1944 has encouraged the Society to organise, in collaboration with the British Astronomical Association, a second series of six lectures. The lecturers and their subjects are given on the next page.

1944	Dec. 1.	Dr. G. C. McVittie.	"The Spiral Nebulæ".
	Dec. 15.	Professor W. M. Smart.	"Some Famous Stars".
1945	Jan. 12.	Dr. R. Stoneley.	"Earthquakes".
	Jan. 26.	Dr. M. A. Ellison.	"The Sun and its Energy".
	Feb. 9.	Dr. R. L. Waterfield.	"The Planet Mars".
	Feb. 23.	Sir H. Spencer Jones.	"Time and its Measurement".

The lectures, which are being reported in *The Observatory*, are again attracting appreciative audiences.

LIST OF PUBLIC INSTITUTIONS AND OF PERSONS WHO HAVE PRESENTED GIFTS TO THE LIBRARY DURING THE YEAR 1944

Abastuman, Astrophysical Observatory of the Georgian S.S.R.
Åbo, Astronomical Observatory
Astronomical Society of South Africa
British Council
British Optical Association
Committee for the Continued Distribution of Astronomical Literature, Harvard College Observatory
Griffith Observatory, Los Angeles
Harvard College Observatory
Imperial Chemical Industries
Institute of Physics
Kirkwood Observatory of Indiana University
Lourenço Marques, Technical Statistical Department
Maria Mitchell Association, Nantucket
Moscow, Academy of Sciences of U.S.S.R.
New York, Academy of Sciences
Peru, Society of Engineers
Society for Research on Meteorites
H.M. Stationery Office
Tadjik Astronomical Observatory, Stalinabad
University of Michigan, W. J. Clements Library
University Tutorial Press
Washington, National Bureau of Standards

Dr. B. J. Bok
Dr. H. van den Bos
Dr. F. E. Brasch
Professor S. Chandrasekhar
Lt.-Colonel B. E. Coke
Professor H. Dingle
The late Sir Arthur Eddington
Mr. A. C. Gifford
Dr. W. Gleissberg
Lady Guest
Mr. A. P. Herbert
Messrs. Hutchinson's
Mr. A. Jaffé
Sir Harold Spencer Jones
Mr. M. A. R. Khan
Dr. R. K. Marshall
Mr. W. O. Matthews
Mr. A. M. Newbegin
The Editors of *The Observatory*
Mr. J. H. Reynolds
Dr. T. J. J. See
Mr. S. W. Shiveshwarkar
The Editors of *Sky and Telescope*
Mr. H. B. Tetlow
Professor S. Vsessviatsky
Mr. H. W. Wood

REPORT OF THE AUDITORS FOR THE YEAR 1944

We have examined the accounts of the Royal Astronomical Society, and we approve of the various items of expenditure shown therein. The official list of Fellows has been checked against the subscriptions received, and we note with satisfaction the continued reduction of the number of subscriptions in arrears.

In the immediate future, the necessity for providing some additional accommodation for the Society's publications, and for the Library, will become more urgent. The unsatisfactory arrangement whereby parts of instruments are dispersed throughout the premises is also due to lack of proper storage facilities, and calls for attention.

We have received from the Assistant Secretary all the information and explanations which we have required, and we gratefully acknowledge her valuable co-operation.

E. G. MARTIN.
J. G. PORTER.

PROGRESS AND PRESENT STATE OF THE SOCIETY

	Patron	Institutional Members	Fellows			Associates	Total
			Compounders	Annual Subscribers	Non-active Fellows		
1944 January 1	1	5	177	562	100	47	892
Since elected	...	...	+1	+32	...	...	...
Election void †	...	...	...	− 1	...	...	...
Deceased, 1944	...	...	−6	−10	−1	...	...
Deceased prior to 1944, death not notified	...	...	−2	− 2	...	...	...
Resigned 1944	...	...	...	− 4	...	...	...
Resigned 1943	...	...	...	− 1	...	...	...
Since compounded	...	...	+9	− 9	...	...	...
Suspense Account—							
Added 1944:							
(*a*) Subns. unobtainable under War conditions	...	...	...	− 5	+ 5	...	...
(*b*) Under Bye-law 26A... ...	...	...	...	− 3	+ 4	...	...
(*c*) Under Bye-law 26B... ...	...	...	...	− 1	+ 4	...	...
Transferred 1944:							
(*a*) From "War conditions" 1943 to Bye-law 26A ...	...	...	...	...	− 1	...	...
(*b*) Ditto to Bye-law 26B	...	...	...	...	− 3	...	...
(*c*) From Non-active 1943 to Active	...	...	...	+ 6	− 6	...	...
1945 January 1	1	5	179	564	102	47	898*

(* As far as can be ascertained under present circumstances.)
(† William S. Mason, elected 1943 April 9, deceased.)

(Nine Associates are also Fellows, and are therefore counted twice in the above table.)

Cash

RECEIVED

	£ s. d.	£ s. d.
Balances, 1944 January 1:—		
In hand of Assistant Secretary, on Petty Cash Account	8 9 6	
At Westminster Bank, on Current Account	731 2 7	
At Westminster Bank, on "B" Account:—		
A. S. Williams Bequest	52 10 0	
At Westminster Bank, on "C" Account:—		
Trust Funds £114 19 10		
Sales of Duplicate Books Fund 4 11 1		
Goodridge Bequest 10 6 0		
	129 7 11	
At Post Office Savings Bank:—		
General Fund £1,590 16 4		
"C" Account 639 1 8		
	2,229 18 0	
At London Savings Bank:—		
Ordinary Department (including £250 A. S. Williams Bequest) £1,073 10 0		
Special Investment Department 541 18 9		
	1,615 8 9	
		4,766 16 9
Dividends on Investments	609 2 4	
Interest on Savings Banks Deposits	91 3 10	
Income Tax refunded: 1943 April–December £160 16 4		
1944 January–April 108 17 8		
	269 14 0	
Sales of Publications:—		
For 1944 £170 9 6		
Due in 1942 (including postages) 5 2 0		
Due in 1943 3 18 0		
1945 in advance 59 18 3		
	239 7 9	
Reprints:—		
For 1944 £11 2 7		
Due in 1942 2 6 8		
Due in 1943 5 3 7		
	18 12 10	
Sales of Photographs and Hire of Slides	14 1 9	
Miscellaneous Receipts:—		
London Mathematical Society £12 0 0		
Assistant Secretary, Pension Contribution 8 0 0		
Gift to General Funds of the Society 1 1 0		
Excess on Contributions 0 7 6		
Postages repaid 12 10 3		
Postages 1945, paid in advance 6 13 0		
British Astronomical Association, 1943 12 10 0		
British Astronomical Association, 1944 37 10 0		
	90 11 9	
		1,332 14 3
Received on Account of Contributions:—		
502 Annual Contributions, 1944	1,054 4 0	
4 Institutional Membership Fees, 1944	8 8 0	
35 Annual Contributions, 1945, in advance	73 10 0	
1 Part Contribution, 1945, in advance	1 0 0	
1 Annual Contribution, 1946, in advance	2 2 0	
29 Admission Fees, 1944	60 18 0	
28 First Contributions, 1944	46 4 0	
Arrears paid off:—		
1939 £2 2 0		
1940 2 2 0		
1941 8 8 0		
1942 18 18 0		
1943 71 8 0		
Admission Fee and First Contribution, 1943 3 3 0		
	106 1 0	
		1,352 7 0
Compositions:—		
Initial	63 0 0	
Reduced	133 7 0	
		196 7 0
"C" Account:—		
Dividends on Investments	161 4 11	
Income Tax refunded: 1943 April–December £29 8 3		
1944 January–April 8 8 5		
	37 16 8	
Interest on Post Office Savings Bank Account	15 19 6	
		215 1 1
Sales of Duplicate Books		13 10 0
Gift to Sales of Duplicate Books Fund		21 17 6
		£7,898 13 7

Account

PAID

	£ s. d.	£ s. d.
Assistant Secretary: Salary £274 9 3		
Inland Revenue: Income Tax on ditto 75 10 9		
	350 0 0	
Assistant Secretary: Pension Premium	24 0 0	
Health and Unemployment Insurance	3 19 6	
Work done for London Mathematical Society, 1943	5 0 0	
Clerical Assistance including National Insurance	74 7 6	
Porter and Wife: Wages and Cleaning £225 4 6		
Inland Revenue: Income Tax on ditto 3 17 6		
	229 2 0	
Porter and Wife: Pension Contribution	13 0 0	
Health and Unemployment Insurance	6 16 11	
		706 5 11
Insurance (general) and Telephone	35 0 3	
War Damage Insurance, paid up to 1944 December 31	35 0 0	
Fidelity Bond	2 10 0	
		72 10 3
Printing, etc.:—		
Monthly Notices (Vol. 103, Nos. 5, 6; Vol. 104, Nos. 1–4)	774 13 8	
List of Fellows	75 13 9	
Reprints	41 3 9	
Miscellaneous	27 19 5	
Photo-engraving	77 10 3	
		997 0 10
Postages and Packing:—		
Monthly Notices, etc.	73 19 9	
Office Postages...	47 15 6	
		121 15 3
A.R.P. Expenditure	56 6 7	
Stationery and Office Expenses	48 4 11	
Heating and Lighting	87 5 0	
Accountant's Fee	21 0 0	
Subscription to Committee on Library Co-operation	1 1 0	
Authorized Travelling Expenses, 1944 ... ... £1 5 0		
Repairs, Fittings and Fixtures 19 8 9		
House Expenses and Laundry 19 11 8		
Expenses of R.A.S. Meetings and Committees 18 0 7		
Miscellaneous Expenditure... ... ... 16 3 5		
Bank Charges and Cheque Books... ... ... 2 1 9		
Library Expenses 0 4 6		
Porter's working uniform 1 19 5		
	78 15 1	
Gold Medal	9 12 6	
		302 5 1
Purchase of Books from Potter Fund		15 8 8
Headley Observatory:—		
Rent of Observatory Paddock £5 0 0		
Insurance of Buildings and Instruments on Site 2 11 6		
Mr. Maskell for care of Site 2 12 0		
Repairs to Buildings 3 0 0		
	13 3 6	
Less Contribution from British Astronomical Association £2 12 6		
Contribution from Mrs. Phillips 0 17 6		
	3 10 0	
		9 13 6
Block Subscription to *The Observatory*		110 0 0
Lectures for the Forces:—		
Printing 5 18 6		
Lecturers' Travelling Expenses 7 8 8		
Porter's Attendance 3 0 0		
	16 7 2	
Less Contribution from British Astronomical Association	7 7 3	
		8 19 11
		2343 19 5
Expenditure on Trust Accounts:—		
Turnor and Horrocks Fund (Library)	19 6 4	
George Darwin Lectureship Fund	40 0 0	
		59 6 4
Purchase of Books from Sales of Duplicate Books Fund		38 4 6
Balances, 1944 December 31:—		
In hand of Assistant Secretary, on Petty Cash Account	5 19 4	
At Westminster Bank, on Current Account, as per Pass Book £733 0 8		
Less Cheques not yet presented... ... ... 292 16 11		
	440 3 9	
At Westminster Bank, on "B" Account (A. S. Williams Bequest)	52 10 0	
At Westminster Bank, on "C" Account:—		
Trust Funds £254 16 6		
Sales of Duplicate Books Fund... ... ... 1 3 8		
	256 0 2	
At Post Office Savings Bank:—		
General Fund 2,140 19 8		
"C" Account 655 1 2		
Staff Pension Fund 250 0 0		
At London Savings Bank:—	3,046 0 10	
Ordinary Department (including £250 A. S. Williams Bequest) £1,100 6 6		
Special Investment Department 556 2 9		
	1,656 9 3	
		5,457 3 4
		£7,898 13 7

Dr. *General Fund Revenue Account*

	£ s. d.	£ s. d.
To Salaries and Wages, including Pension Premiums and National Insurance		618 18 5
„ Clerical Assistance, including National Insurance		74 7 6
„ Insurance and Telephone (after adjusting Reserves)		42 0 3
„ War Damage Act, 1941, Part II: Premiums to 1944 December 31		52 10 0
„ Printing, etc. (after adjusting Reserves)		882 0 10
„ Posting and Packing (after adjusting Reserves)		102 2 9
„ *General Expenses* (*after adjusting Reserves*) :—		
Stationery and Office Expenses	46 4 11	
Lighting and Heating	101 5 0	
Travelling Expenses	1 5 0	
Subscription to Committee on Library Co-operation	1 1 0	
Accountants' Fee	21 0 0	
A.R.P. and Fire Watchers' Expenses	52 16 7	
Gold Medal	9 12 6	
Repairs and Cleaning of Fittings and Fixtures...	69 8 9	
Sundries	58 16 4	
		361 10 1
„ Block Subscription to *The Observatory*		110 0 0
„ Purchase of Books from Potter Fund...		15 8 8
„ Headley Observatory, Expenses *less* Refunds		8 8 6
„ Lectures for the Forces, Expenses *less* Refunds		8 3 7
„ Annual Reserve for Repairs		40 0 0
„ Reserve for Replacement of Photographic Slides and Prints ...		25 0 0
„ Staff Pension Fund: Amount set aside for year		150 0 0
„ Net Revenue one year to date transferred to Balance Sheet... ...		169 4 1
		£2,659 14 8

One Year to 1944 December 31 *Cr.*

	£ s. d.	£ s. d.	£ s. d.
By *Amounts received from Fellows, viz.:—*			
1 Arrear for 1939	2 2 0		
1 „ „ 1940	2 2 0		
4 Arrears „ 1941	8 8 0		
9 „ „ 1942	18 18 0		
34 „ „ 1943	71 8 0		
1 Arrear, Admission Fee and First Contribution, 1943	3 3 0		
502 Annual Contributions for 1944 (including 8 from Fellows deceased 1944)	1,054 4 0		
4 Institutional Membership Fees	8 8 0		
20 Prepayments for 1944	42 0 0		
		1,210 13 0	
29 Admission Fees	... ...	60 18 0	
1 „ Fee prepaid	... ...	2 2 0	
28 First Contributions	... ...	46 4 0	
1 „ Contribution prepaid	... ...	2 2 0	
Composition Fees:—			
Initial Fees	63 0 0		
Reduced Fees...	133 7 0		
	196 7 0		
Less Transferred to Reserve Account ...	196 7 0		
	— — —		
Add Amount brought to Credit for the year	61 4 8		
		61 4 8	
			1,383 3 8
„ Interest and Dividends received (gross)		864 5 8	
„ Interest on Bank Deposit Accounts received		91 3 10	
			955 9 6
„ Sales of Publications, Photographs and Miscellaneous Receipts for the year			321 1 6
			£2,659 14 8

Note.—Fellows' 1944 *Contributions not received were:—*

59 Unobtainable under War conditions	£123 18 0
29 Waived under Bye-law 26A	60 18 0
14 Waived under Bye-law 26B	29 8 0
22 Others unpaid at 1944 December 31	46 4 0
3 Admission Fees and First Contributions, ditto	9 9 0
1 Institutional Membership Fee, ditto	2 2 0
Total for the year	£271 19 0

This amount has been added to the Suspense Account and is not included in this Revenue Account.

Balance Sheet

LIABILITIES

	£	s.	d.	£	s.	d.
½ Contribution for 1945, paid in 1943	1	1	0			
35 Contributions for 1945, paid in 1944	73	10	0			
1 Part Contribution for 1945, paid in 1944	1	0	0			
1 Contribution for 1946, paid in 1944	2	2	0			
				77	13	0
Sundry Creditors for Accounts due but not presented				419	5	0
Reserve for Repairs and Maintenance:—						
As at 1943 December 31	120	0	0			
Add Set aside 1944	40	0	0			
				160	0	0
Reserve for Replacements of Photographic Slides and Prints:—						
Amount set aside in 1944	25	0	0			
Add Transfer by resolution of Council from Franklin-Adams Charts	170	7	8			
				195	7	8
Trust Funds:—						
Capital as at 1943 December 31	5,257	0	3			
Less Goodridge Bequest, Capital transferred to General Fund...	50	0	0			
	5,207	0	3			
Income Balances at 1944 December 31	909	7	3			
Income Tax on Trust Funds, 1944 April–December, not yet refunded	21	14	2			
				6,138	1	8
Grove-Hills Fund (Capital)	1,480	2	2			
Less transferred to General Fund	1,480	2	2			
				–	–	–
Sales of Duplicate Books Fund:—						
In hand at 1943 December 31	4	11	1			
Add Received for Duplicate Books sold	13	10	0			
Received by Gift to Fund	21	17	6			
	39	18	7			
Less Books purchased, 1944	38	4	6			
				1	14	1
Composition Fees Reserve Fund:—						
As at 1943 December 31	824	4	4			
Received in 1944	196	7	0			
	1,020	11	4			
Less 6% transferred to Current Account	61	4	8			
				959	6	8
Franklin-Adams Charts:—						
As at 1943 December 31	170	7	8			
Less transferred to Reserve for Replacements of Photographic Slides and Prints	170	7	8			
				–	–	–
Advance Receipts for Publications, 1945	59	18	3			
Advance Receipts for Postages, 1945	6	13	0			
				66	11	3
Credits still in hand from 1939				0	12	3
Staff Pension Fund:—						
As at 1943 December 31	100	0	0			
Add Amount set aside in 1944	150	0	0			
				250	0	0
General Fund:—						
As at 1943 December 31	21,263	3	4			
Add Transfer by resolution of Council from Grove-Hills Fund 1,480 2 2						
Transfer from Goodridge Bequest (including £10, 6*s.* 0*d.* Income Balance) 60 6 0						
	1,540	8	2			
	22,803	11	6			
Add Excess of Revenue over Expenditure, 1944...	169	4	1			
				22,972	15	7
				£31,241	7	2

To the Fellows of THE ROYAL ASTRONOMICAL SOCIETY.

We have examined the above Balance Sheet with the Books and Vouchers relating thereto explanations given to us.

We have verified the Securities representing the Investments and have found them to be

1944 *December* 31

ASSETS

	£ s. d.	£ s. d.
Sundry Debtors, 1944		34 12 8
Investments of General Fund, valued as at 1922 December 29 or subsequent cost		20,374 11 1
Investments of Trust Funds, valued at cost		5,207 0 3
Income Tax, 1944 April–December, deducted at source, not yet refunded:—		
General Fund	146 5 8	
Trust Funds	21 14 2	
		167 19 10
Sundry Balances, as per Cash Account		5,457 3 4
		£31,241 7 2

Note.—Fellows' Contributions (including 1 Institutional Membership Fee) and 3 Admission Fees unpaid at 1944 December 31: £963, 18s. 0d. This amount represents the total of the Suspense Account and is not included in this Balance Sheet.

and certify it to be correctly drawn up therefrom and in accordance with the information and in order.

SUFFOLK HOUSE,
5 LAURENCE POUNTNEY HILL, LONDON, E.C. 4,
1945 March 5

SHARP, PARSONS & CO.,
Chartered Accountants.

INVESTMENTS

As at 1944 December 31

General Fund

£2000 Swansea Corporation 3½ per cent. Stock.
£5125 London, Midland and Scottish Railway 4 per cent. Debenture Stock.*
£750 London, Midland and Scottish Railway 4 per cent. Preference Stock.*
£2400 Gas Light and Coke Co. 3 per cent. Consolidated Debenture Stock.*
£2000 Commercial Gas Co. 3 per cent. Debenture Stock.*
£496 Consolidated 4 per cent. Stock, 1957.
£1035 Agricultural Mortgage Corporation, Ltd., 4½ per cent.Debenture Stock, 1961–91.*
£1000 Hull Corporation 4½ per cent. Redeemable Stock, 1952–72.
£1000 Central Electricity Board 4½ per cent. Stock, 1957–82.*
£700 Birmingham Corporation 3 per cent. Inscribed Stock, 1947.
£2280, 5*s*. 3*d*. War Loan 3½ per cent. Inscribed Stock.
£500 New South Wales 4 per cent. Stock, 1942–62.*
£1156, 1*s*. 5*d*. Metropolitan Water Board 3 per cent. "B" Stock.
£500 National Defence Loan, 1954–58, 3 per cent. Bonds.
£500 National War Bonds 2½ per cent., 1946–48.
£2118, 3*s*. 5*d*. Savings Bonds 3 per cent., 1960/1970. (A Holding.)
£695, 16*s*. 0*d*. Conversion Loan 3½ per cent., 1961.

Trust Funds

£1004 Consolidated 4 per cent. Stock, 1957.
£965 Agricultural Mortgage Corporation, Ltd., 4½ per cent. Debenture Stock, 1961–91.*
£491, 10*s*. War Loan 3½ per cent. Inscribed Stock.
£1160, 16*s*. 3*d*. War Loan 3½ per cent. Inscribed Stock.
£542, 18*s*. 2*d*. Savings Bonds 3 per cent., 1960/1970. (B Holding.)
£1122, 19*s*. 6*d*. Savings Bonds 3 per cent., 1960/1970. (C Holding.)

* *Taxed at source.*

GIFTS TO THE GENERAL FUNDS AND PROPERTY OF THE SOCIETY

The John Lee Gift : In 1836 John Lee, Esq., LL.D., gave the Advowson of the living of Hartwell; in 1844 he gave the Advowson of the living of Stone, Bucks. In 1879 these Advowsons were repurchased by his heir, Edward Lee, Esq., for £700.

The Lawson Bequest (1856): Henry Lawson, Esq., bequeathed to the Society the sum of £200, free of legacy duty.

The Carrington Bequest (1876): R. C. Carrington, Esq., F.R.S., bequeathed to the Society £2000 Consols.

The Lambert Bequest (1877): C. J. Lambert, Esq., presented to the Society the sum of £500 free of legacy duty, being part of a sum of money bequeathed by his father, Charles Lambert, Esq., for scientific purposes.

The McClean Bequest (1905): Frank McClean, Esq., LL.D., F.R.S., bequeathed to the Society the sum of £2000, free of legacy duty.

The Farrar Bequest (1906): The Rev. A. S. Farrar, D.D., bequeathed to the Society the sum of £100, free of legacy duty.

The Parsons Gift (1922): The Hon. Sir Charles Parsons, K.C.B., F.R.S., gave to the Society £2500 War Stock 1929–47, in memory of his father, the 3rd Earl of Rosse, who made the 6-foot reflector, and who died 1867 October 31.

The Grove-Hills Bequest (1922): Colonel E. H. Grove-Hills, C.M.G., F.R.S., bequeathed to the Society, free of legacy duty, his collection of early astronomical and mathematical books up to the year 1700, together with a sum of £250 to cover the expenses incurred by the Society in connection with the books.

The Grove-Hills Fund (1922): In 1922 the Treasurer, Colonel Grove-Hills, collected by his private efforts, with the approval of the Council, a Special Fund to meet the immediate financial difficulties of the Society. The total amount received from all sources (including dividends on the investments representing the fund) has been £1913, 1*s.* 11*d.*, of which £1480, 2*s.* 10*d.* has been invested and is now represented by £535 Agricultural Mortgage 4½ per cent., £423, 15*s.* 11*d.* War Stock 3½ per cent., and £695, 16*s.* Conversion Loan 3½ per cent. 1961.

The Lindemann Bequest (1931): A. F. Lindemann, Esq., bequeathed to the Society the sum of £1000, free of legacy duty.

The Archdeacon Potter Bequest (1933) (*see below*).

The Goodridge Bequest (1936): Captain J. J. L. Goodridge, who died 1936 March 13, bequeathed to the Society the sum of £50, free of legacy duty. In 1937 the bequest was invested in £49, 0*s.* 4*d.* War Stock 3½ per cent.

The Herbert Spencer Bequest (1936): Herbert Spencer, Esq., who died in 1903, nominated the Royal Astronomical Society as one of twelve Learned Societies to be eventual

beneficiaries of his residuary estate. His estate was wound up in 1936, and the Society's share of the residue amounted to £1241. The conditions of acceptance of the legacy were that the sum received should be spent in certain specified ways by the Governing Body within five years of the date of payment, and might not be used in any way for purposes of endowment. The bequest was finally expended during 1941.

The Lindley Bequest (1937): Miss Julia Lindley bequeathed to the Society the sum of £1000, free of legacy duty, which was received from the Public Trustee in the form of £1156, 1*s.* 5*d.* Metropolitan Water Board 3 per cent. "B" Stock.

The Stanley Williams Bequest (1939): A. Stanley Williams, Esq., who died 1938 November 21, bequeathed to the Society all his astronomical instruments, books, maps, photographs, manuscripts, etc., together with the sum of £200, free of legacy duty, for the reduction or publication of his observations of variable stars; and also a further sum of £100, free of legacy duty, for the furtherance of astronomy in general or of the Society in particular, in such manner as the Council of the Society may think fit. No expenditure from the fund has been made up to 1944 December 31.

SPECIAL FUND

The Archdeacon Potter Fund (1933): Archdeacon Beresford Potter, who died 1931 May 10, bequeathed to the Society a 3/88th share of his residuary estate. This legacy was received in 1933, and now stands invested in £300 3½ per cent. War Stock, the cash balance of £17, 15*s.* 2*d.* being expended on the library in 1934. The Council resolved to allocate the dividends from this fund for the purposes of the library.

	£	*s.*	*d.*		£	*s.*	*d.*
1944 Jan. 1. Balance of Fund ...	56	3	9	1944. Purchase of Books ...	15	8	8
1944. Dividends, War Stock 3½ per cent.	10	10	0	1944 Dec. 31. Balance of Fund	51	5	1
	£66	13	9		£66	13	9

TRUST FUNDS

The Lee and Janson Fund (1834 and 1879): In 1834 John Lee, Esq., LL.D., gave £100, and in 1879 T. C. Janson, Esq., bequeathed £200, the interest to be given to the widow or orphan of a deceased Fellow. These amounts now stand in £309, 16*s.* 3 per cent. Savings Bonds, 1960/1970.

	£	*s.*	*d.*			£	*s.*	*d.*
1944 Jan. 1. Balance of Fund ...	37	9	11	1944 Dec. 31. Balance of Fund:—				
1944. Dividends, 3 per cent. Savings Bonds	6	19	6	In P.O. Savings Bank	£35 12 7			
Income Tax, 1943 April–1944 April, refunded	4	9	0	At Bank	14 3 6			
						49	16	1
Interest on P.O. Savings Bank Deposit	0	17	8					
	£49	16	1			£49	16	1

The Turnor Fund and the Horrocks Memorial Fund (1853 and 1876): In 1853 the Rev. Charles Turnor, M.A., bequeathed a sum of £500, which now stands in £430, 10*s.* 4*d.* 3 per cent. Savings Bonds, 1960/1970. In 1876 the Society received a sum of £38, 15*s.*, the unexpended balance of a fund collected for the purpose of erecting a memorial in Westminster Abbey to Jeremiah Horrocks: to this the Society added the sum of £55, 15*s.*, and the whole now stands in £95, 13*s.* 2*d.* 3 per cent. Savings Bonds, 1960/1970. The interest on these funds is to be used in the purchase of books for the library.

	£	s.	d.		£	s.	d.
1944 Jan. 1. Balance of Fund ...	4	4	2	1944. Purchase of Books ...	19	6	4
1944. Dividends, 3 per cent. Savings Bonds	11	16	9	1944 Dec. 31. Balance of Fund...	4	5	8
Income Tax, 1943 April–1944 April, refunded	7	11	1				
	£23	12	0		£23	12	0

The Hannah Jackson (née Gwilt) Fund (1861): In 1861 Mrs. Hannah Jackson (*née* Gwilt) gave £300 Consols, which now stands in £287 3 per cent. Savings Bonds, 1960/1970; the interest to be given in medals or other awards in accordance with the terms of the Trust.

	£	s.	d.		£	s.	d.
1944 Jan. 1. Balance of Fund ...	27	13	10	1944 Dec. 31. Balance of Fund...	38	5	3
1944. Dividends, 3 per cent. Savings Bonds	6	9	0				
Income Tax, 1943 April–1944 April, refunded	4	2	5				
	£38	5	3		£38	5	3

The Harry Watson Memorial Fund (1923): In 1920 Mrs. Watson presented to the Society the sum of £300 as a memorial to her late husband, Lieut.-Col. Harry James Watson, F.R.A.S., the interest on this sum to be used for the purchase of books for the library, such books to be indicated by a special book-plate. This gift now stands invested in £542, 18*s.* 2*d.* 3 per cent. Savings Bonds, 1960/1970. In 1923 Mrs. Watson bequeathed a further sum of £958, 17*s.* to the Society, which now stands invested in £965 Agricultural Mortgage 4½ per cent. Stock. The Council resolved that these two sums should together constitute a Trust Fund, to be designated *The Harry Watson Memorial Fund*, to be used for the purchase and binding of books.

	£	s.	d.		£	s.	d.	£	s.	d.
1944 Jan. 1. Balance of Fund ...	246	10	10	1944 Dec. 31. Balance of Fund:—						
1944. Dividends, Agricultural Mortgage 4½ per cent. ...	21	14	4	In P.O. Savings Bank	£228	1	6			
Dividends, 3 per cent. Savings Bonds	16	5	8	At Bank	83	14	9			
Income Tax, 1943 April–1944 April, refunded	21	14	2					311	16	3
Interest on P.O. Savings Bank Deposit	5	11	3							
	£311	16	3					£311	16	3

The George Darwin Lectureship Fund (1926): In 1926 Sir James Jeans presented to the Society the sum of £1000 for the endowment of an annual lectureship, to be called *The George Darwin Lectureship*, the lecture to be on some subject of interest to astronomers, preference being given, in electing a lecturer, to one normally resident outside the British Isles.

This sum now stands in £1004 Consolidated 4 per cent. Loan. The income is annually applied to the purposes of the Trust in accordance with the terms of the Deed of Gift.

	£ s. d.		£ s. d.
1944 Jan. 1. Balance of Fund ...	144 8 6	1944 Oct. Lecture Fee	40 0 0
1944. Dividends, Consolidated 4 per cent. Loan	40 3 2	1944 Dec. 31. Balance of Fund:— In P.O. Savings Bank £126 12 10	
Interest on P.O. Savings Bank Deposit	3 1 9	At Bank 21 0 7	
			147 13 5
	£187 13 5		£187 13 5

The A. G. Stillhamer Trust (1937): A. G. Stillhamer, Esq., of Bloomington, Illinois, left all his property outright to Miss Maude S. Capps, of Bloomington; but on account of certain personal memoranda and conversation between Mr. Stillhamer and Miss Capps, the latter resolved to carry out what she believed to have been Mr. Stillhamer's wishes by the payment to the Royal Astronomical Society of the sum of 2500 dollars in cash, the conditions of acceptance being that the principal is to remain intact in the endowment fund of the Society, and the income therefrom to be used annually * to pay expenses of scientific research or to purchase definite scientific instruments for use in scientific instruction or research. The bequest has been invested in £491, 10*s.* War Stock 3½ per cent.

	£ s. d.		£ s. d
1944 Jan. 1. Balance of Fund ...	105 16 2	1944 Dec. 31. Balance of Fund:— In P.O. Savings Bank £95 8 8	
1944. Dividends, War Stock 3½ per cent.	17 4 0	At Bank 29 18 0	
Interest on P.O. Savings Bank Deposit	2 6 6		125 6 8
	£125 6 8		£125 6 8

The E. W. Brown Trust (1939): E. W. Brown, Esq., M.A., Sc.D., F.R.S., who died in 1938, bequeathed to the Society the sum of five thousand dollars, and desired that the income from the bequest should be used for assistance in the calculation of accurate orbits of the bodies of the solar system, such income as should not be used for this purpose being used for the general purposes of the Society. The bequest was received in 1939 July, and was invested in £1160, 16*s.* 3*d.* War Stock 3½ per cent.

	£ s. d.		£ s. d.
1944 Jan. 1. Balance of Fund ...	187 9 1	1944 Dec. 31. Balance of Fund:— In P.O. Savings Bank £168 15 2	
1944. Dividends, War Stock 3½ per cent.	40 12 6	At Bank 63 8 9	
Interest on P.O. Savings Bank Deposit	4 2 4		232 3 11
	£232 3 11		£232 3 11

* Miss Capps, subsequently to the initial conditions of the Trust, agreed to the income not being expended annually.

OBITUARY NOTICES

STANLEY PHILIP BENGE, officially reported missing, joined the R.A.F. in 1941, became sergeant navigator and eventually pilot officer, navigating first a Beaufighter and finally a Mosquito on night-fighting operations.

He took up teaching as his profession and had been teaching for nearly twenty years under the London County Council, specializing in science, music and drawing. He interested himself in clay-modelling and had a great gift for training and conducting choirs. He was keenly interested in astronomy, especially in the photographic side of the subject.

His exceptional fitness of body and his knowledge of astronomy helped him to serve his country in the active rôle of navigator in a night fighter, and it was whilst serving in this capacity that he was brought down in combat over the sea on 1943 October 8, three weeks before his fortieth birthday.

He married Miss Daisy Morgan, a London teacher, who survives him.

He was elected a Fellow of the Society on 1936 May 8.

C. F. N. POWELL.

MARY ADELA BLAGG, whose death occurred on 1944 April 14, was the eldest daughter of the late Charles Blagg, a solicitor of Cheadle, North Staffordshire. She was born at Cheadle on 1858 May 17, and, apart from short absences, lived there all her life.

She was educated at home and at a private boarding-school in London. She did not go to college or follow any profession, but performed much voluntary social and religious work, which included the care of Belgian refugee children during the 1914–1918 war. Chess was one of her hobbies, and until a few weeks of her death (she was an invalid through heart trouble during the last eight years) used to work out the problems given in a Sunday newspaper. A natural aptitude for mathematics enabled her to enlarge her knowledge of this subject by borrowing her brothers' school books, and when the necessity arose she had no difficulty in manipulating harmonic analysis. A leaning towards science was no doubt latent in her, but it was not until she had already arrived at middle age that she became seriously interested in astronomy as a result of attending a course of University Extension lectures given at Cheadle by Mr. J. A. Hardcastle. He inspired her to attempt original work, and suggested a line of investigation in which he himself was interested, namely selenography.

At the commencement of the present century the nomenclature of lunar formations was in a very unsatisfactory state, owing to the many discrepancies apparent between the maps of the principal selenographers, such as Beer and Mädler, Schmidt and Neison. Not infrequently the same name was used to denote different formations, or different names were attached to the same object. In 1905, S. A. Saunder, who was doing pioneer work in determining accurate positions of points on the lunar surface, drew the attention of the Royal Astronomical Society to the desirability of a uniform lunar nomenclature, whereupon Professor Turner brought the matter before the Royal Society and, representing that body, before the International Association of Academies meeting at Vienna in 1907. This resulted in the appointment of an international committee, of which Saunder and Turner were members, and Saunder was fortunate in obtaining the collaboration of Miss Blagg in collating the names given to all the lunar formations in the maps mentioned above. This work was admirably carried out by Miss Blagg, and a *Collated List* was published in 1913 under the auspices of the International Association of Academies. When the International Astronomical Union was founded in 1920, the

matter was taken up by the Lunar Commission of that body, consisting of Miss Blagg and Messrs. Bigourdan, W. H. Pickering and Puiseux, under the presidency of Professor Turner, and the *Collated List* formed the basis for discussion at the Cambridge meeting (1925) and at Leyden (1928), where Miss Blagg submitted further lists showing the measure of agreement and the discrepancies between the older selenographers, whilst Dr. Müller, of Vienna, presented lists of names used by later observers, including Lamèch, Krieger, Müller and Wilkins. At this meeting a sub-committee was appointed, consisting of Miss Blagg and Dr. Müller, to prepare a definitive list of names. The work was accomplished within three years and presented at the following meeting of the I.A.U. at Cambridge, Mass. (1932), where provision was made for its publication, and *Named Lunar Formations*, by Mary A. Blagg and K. Müller (Percy Lund, Humphries & Co. Ltd., London, 1935), is now the standard authority for all matters of lunar nomenclature.

Of no less importance than her lunar work, and carried on more or less simultaneously with it, was Miss Blagg's work on variable stars. In 1907 the manuscript notebooks containing Mr. Joseph Baxendell's original observations of variable stars were put into the hands of Professor H. H. Turner with a view to their reduction and publication. Most of the observations were still in day-book form; there were difficulties in the identification of the numerous comparison stars used, and Professor Turner, finding that alone he could make little headway, appealed for "skilled volunteer assistance . . . in making this mass of valuable material ready for publication as soon as possible" (*M.N.*, **67**, 316). The appeal was answered by Miss Blagg, and there followed a long and fruitful collaboration which resulted in the publication of a series of ten papers which appeared in *Monthly Notices*, Vols. **73–78** (1912–18), under their joint authorship. In a concluding note (*Monthly Notices*, **78**, 528) Professor Turner says "practically the whole of the work of editing has been undertaken by Miss Blagg. The difficulties of identification have been noted frequently; they could scarcely have been overcome without her patience and care".

The interest in variable stars awakened in her, and the experience gained through editing Baxendell's observations, led Miss Blagg to undertake on her own account a study of the eclipsing binary β Lyræ based on observations made by members of the Variable Star Section of the British Astronomical Association and by Sawyer, which occupied three papers in *Monthly Notices* (Vols. **84**, **85** and **88**), and also studies of the Long Period Variables RT Cygni, V Cassiopeiæ and U Persei, using observations by Mr. A. N. Brown (*Monthly Notices*, Vols. **89**, **90** and **91**). She deduced new elements for these stars and harmonically analysed the light curves obtained from the observations.

Miss Blagg was of a modest and retiring disposition, in fact very much of a recluse, and was rarely seen at meetings, etc. She attended the Cambridge meeting of the International Astronomical Union (1925), her first "public appearance", and the meeting at Leyden three years later. The value of her contribution to astronomical progress was, no doubt, partly due to her willingness to work under the direction of others—S. A. Saunder, Professor Turner and Professor E. W. Brown—and also to her willingness to undertake a large amount of spade work, and to the intelligent care she bestowed on what must often have been tedious detail. But she was far more than a mere amanuensis or compiler of facts, which is evident in her own papers communicated to this Society. In all her work she displayed not only skill and sound judgment, but also originality and courage.

Taking up astronomy rather late in life and without any special preparation, she nevertheless left her mark on the science, and her name will go down to posterity. The International Lunar Committee, on the proposal of M. Lamèch, has ordained that the name of Blagg be assigned to a small lunar crater, thus ensuring for her a well-deserved place among the lesser immortals.

P. M. RYVES.

JOHN BRITTAIN was born in the year 1860 at Pyle, Glamorganshire, and died in his eighty-third year on 1943 January 24.

In 1870 his parents went to Australia, and the family settled at Mount Pleasant where Mr. Brittain spent his schooldays. He then passed on to the Mount Pleasant School of Mines where, as the result of his success in his studies, he was appointed lecturer in astronomy and microscopy. Mr. Brittain showed a wide practical interest in his studies—he became a miner for a time, practised photography, and served as Vice-President of the School of Mines Field Naturalists Club. He served his town in more than one capacity, first as municipal valuer and later as health inspector until his failing health prompted him to retire in 1941 August. During all this time Mr. Brittain was superintendent of the Municipal Observatory at Mount Pleasant and contributed regular articles on astronomy and science generally to the Australian newspapers. He was elected a member of the Astronomical Society of France.

Mr. Brittain served as an officer in the "Old Third" Battalion and acted as honorary secretary of the Ballarat East recruiting committee during the first world war.

He was a keen churchman and a prominent Mason, having been past master, ex-member of Grand Lodge and chaplain.

His widow, three sons and daughter survive him.

He was elected a Fellow of the Society on 1910 December 9.

ALEXANDER EUGEN CONRADY was born at Burscheid, near Cologne, on 1866 January 27, and died in London on 1944 June 16 at the age of seventy-eight.

He was the fifth in a family of seven children, his father being descended from a long line of village schoolmasters.

He attended schools in Burscheid and Barmen, later going to Bonn University, where he studied mathematics under Lipschitz, physics under Clausius, chemistry under Kekulé and astronomy under Schönfeld. He left his studies for a year in 1886 to travel for his father's firm, during which time he first came to England and met his lifelong friend and benefactor, the late Mr. George W. Brown, of Leeds.

He then returned to Bonn for one and a half years (1887–88) as research assistant to the organic chemist Wallach, his work consisting chiefly of physical measurements. One paper he wrote during that period on atomic refractions provided a series of standard data which were not superseded until 1912.

About this time, his extreme distaste for the existing German regime, together with a most discouraging series of breakdowns in health, led him to give up a promising academic career for a period of travel. He went first to Nova Scotia and later to North Carolina as a mining chemist, to supervise some of Mr. Brown's many enterprises, after which he decided to take up his residence in England. In 1901 he married Annie Bunney of Harefield, Middlesex, and in 1903, soon after the birth of the first of his four daughters, he became naturalized, and remained to the end a loyal and devoted citizen of his adopted country.

With the financial support of Mr. Brown, he founded in 1891 a small factory in Keighley, primarily to make models of new machines, but the establishment was later enlarged to manufacture dynamos, arc lamps and other electrical devices. Finally, after moving to London in 1896, Conrady commenced the small-scale manufacture of microscope objectives, made to his own designs. This activity was at first purely a hobby, but it led in 1902 to his employment by W. Watson & Co. as their scientific adviser and optical designer. His work was concerned mainly with microscopes, but it included also some photographic objectives and service instruments such as submarine periscopes.

In 1917, when the Technical Optics Department was established at the Imperial College of Science and Technology in South Kensington, Conrady left Watson's to become Professor of Optical Design. He proved to be an instinctive teacher, and for

fifteen years his lectures were the inspiration of a new generation of young lens designers. In 1927 he published the first part of his book, *Applied Optics and Optical Design*, which is the first and only textbook of lens design written with the needs of the complete beginner constantly in mind. It is not too much to say that this remarkable book has been a major contributory factor in the development of new optical-sighting devices during the present war, both in England and America, where it has been eagerly studied by physicists, engineers and astronomers who are unexpectedly obliged to design new devices employing optical systems. The second part of the book was never published, although a considerable part of the manuscript has been written and is in publishable form.

Conrady's interest in lenses began as early as 1893, as a by-product of his desire to possess a fair-sized astronomical telescope. He at once noticed that ordinary objectives invariably yield a smaller star image than simple geometrical theory would indicate, and within a few months he had independently discovered the Rayleigh limit of permissible aberration, based on the conception of differences in the optical path of various rays passing through the lens. He expanded this approach to cover all the aberrations, including chromatic, and published his findings in a series of papers in *Monthly Notices*, 1904–6. After he began formal teaching at the Imperial College he elaborated a more geometrical approach, which he also published in *Monthly Notices* in 1918 and 1919, but his earlier treatment has the greater appeal because of its essential simplicity and fundamental relation to the light-waves themselves. He was awarded the Traill-Taylor medal of the Royal Photographic Society in 1920, his address at that time being entitled *The Present State of Photographic Optics*.

He was elected a Fellow of the Society in 1902, and one of the greatest pleasures of his life was to attend the monthly meetings.

R. KINGSLAKE.

ARTHUR STANLEY EDDINGTON was born on 1882 December 28 at Kendal, Westmorland, the second child and only son of Arthur H. Eddington, the headmaster of the Friends' School in that town. At a very tender age his interest in numbers, a sign of the budding mathematician, began to reveal itself. On the death of his father the family moved to Weston-super-Mare, and there, at Bryn Melyn School, he received his early education. Proceeding to Owens College, Manchester, in 1898 October, he took the first course in physics during his first year. In the following session he entered on the Physics Honours course, and three years later took his degree at the head of the list of the whole Victoria University (then comprising Manchester, Liverpool and Leeds), in a particularly brilliant year. Most of the teaching in physics at that time was given by C. H. Lees, but Eddington also attended the lectures of Lamb and Schuster. He took his part in the social and athletic life of Dalton Hall (one of the Halls of Residence of Owens College) and was a regular member of the 2nd football eleven, occasionally playing for the first. Later, when at the Royal Observatory, he played hockey for the Observatory Hockey Club. Throughout his life he enjoyed cycling; G. C. Simpson relates how one day Eddington returned full of glee from a cycle ride, on which he had used a cyclometer for the first time, saying that while checking the cyclometer against the milestones, he had found himself putting on speed to get to the next stone before the cyclometer recorded the mile!

In 1902 he entered Trinity College, Cambridge, with an entrance scholarship in Natural Science. In the Mathematical Tripos of 1904 he was Senior Wrangler, and in the following year was placed in the first division of the first class of Part II of the Tripos. In 1907 he was Smith's Prizeman, and in the same year he was elected a Fellow of Trinity College. It is probable that he had intended to make physics his life-study, for he had spent the Michaelmas Term, after taking Part II of the Mathematical Tripos, working in the Cavendish Laboratory on the subject of thermionic emission. But in

1906 a vacancy occurred in the post of Chief Assistant at the Royal Observatory, Greenwich, caused by the appointment of F. W. Dyson to succeed Copeland as Astronomer Royal for Scotland. The post was offered by the Astronomer Royal, Sir William Christie, to Eddington and the offer was accepted. Thus Eddington came to Greenwich and astronomy became his first interest. Astronomy is under a great debt of gratitude to Christie for his judicious choice. Eddington would have made his mark in any field of work that captured his interest; fortunate indeed it was for astronomy that the opening at Greenwich presented itself when Eddington was ripe for it.

Eddington spent the next seven years at Greenwich, taking his share in the routine observations. He thus obtained experience in observational astronomy and a familiarity with its problems which were to stand him in good stead. Though his interests were always primarily in theoretical investigations, he was able to appraise the value of observations and to test theoretical conclusions by means of the data provided by observations. While at Greenwich he discussed the observations made with the Airy reflex tube for the determination of latitude variation. This instrument, though ingenious in principle, had given anomalous and disappointing results. As a result of Eddington's critical analysis, it was decided to discontinue these observations and to employ the Cookson floating zenith telescope, loaned by the Cambridge Observatory, for the determination of the variation of latitude and the constant of aberration. This telescope, designed by Bryan Cookson and used by him in a programme of observations at Cambridge, had not given results of the expected precision. Cookson's untimely death had prevented further investigations. Eddington changed the method of observation so that the star trails were photographed only in a small central region of each plate: Cookson had not used this method, though he had considered it as an alternative. A new programme of observation was planned and the preliminary results, discussed by Eddington shortly before he left Greenwich, proved to be highly satisfactory. Observations according to this programme were continued for more than twenty-five years.

Another observational problem with which he dealt was the mode of formation of the envelopes of Morehouse's Comet, based on the measurement of the excellent series of photographs of the comet obtained at Greenwich.

Eddington became interested, soon after he commenced work at Greenwich, in the problem of star-streaming. Kapteyn had announced, a few years previously, his discovery of the two star-streams. He had found that the motions of the stars, after eliminating the solar motion, could not be represented by the hypothesis of random motion, but that the stars tend to move in two favoured directions, the motions in each of these directions being distributed in a haphazard manner. This peculiarity of the individual motions was found to prevail throughout the heavens and was not confined to certain regions. The method of investigation used by Kapteyn was a graphical method based on the shape of the polar distribution curves of the proper motions of the stars in limited areas of the sky; by trial and error, a combination of the two streams was found which gave a satisfactory representation of the distribution of the observed proper motions.

In a paper published in 1907 Eddington treated Kapteyn's hypothesis by an elegant mathematical method, which was simple in practical application, and which enabled the constants of the two streams to be derived. He discussed first the proper motions of the stars in Groombridge's Catalogue, which had been derived a few years previously by Dyson and Thackeray in connection with their new reduction of this catalogue. Then, after the publication of Boss's *Preliminary General Catalogue*, he analysed the proper motions of the stars contained in it, which are distributed over the whole sky. Eddington's thorough and more precise method of discussion confirmed and amplified Kapteyn's conclusions. In 1914 he published his first book, *Stellar Movements and the Structure of the Universe*. This work contained an account of his own researches, but this was made subservient to the wider aim of giving an account of the many recent discoveries in sidereal astronomy and co-ordinating them to present, so far as was possible at the time,

a coherent description of the stellar universe. Eddington did not limit himself to what had been definitely proved. In the preface he wrote: "There can be no harm in building hypotheses, and weaving explanations which seem best fitted to our present partial knowledge. These are not idle speculations if they help us, even temporarily, to grasp the relations of scattered facts, and to organize our knowledge". At that time, the opinion was being strongly held that the spiral nebulæ were members of the galactic system and not island universes. Eddington's comment on this was as follows: "If the spiral nebulæ are within the stellar system, we have no notion what their nature may be. That hypothesis leads to a full stop. . . . If, however, it is assumed that these nebulæ are external to the stellar system, that they are in fact systems co-equal with our own, we have at least an hypothesis which can be followed up, and may throw some light on the problems that have been before us. For this reason the 'island universe' theory is much to be preferred as a working hypothesis; and its consequences are so helpful as to suggest a distinct probability of its truth". This quotation illustrates Eddington's general attitude and also his intuition. The final chapter was a first attempt at the study of the dynamics of the stellar system; he showed that the apparent analogy of the stars with a gaseous system of molecules must be rejected and that the stars must be considered as describing paths under the general attraction of the stellar system without interfering with one another. In subsequent papers some further progress was made in the development of the new subject of stellar dynamics.

This book was a great stimulus to the further development of the subjects which it discussed. It raised a number of questions, some of which have since been answered, whilst to others no answer has yet been found. In each of the main fields in which Eddington worked he followed the same plan of publishing a connected account of the new advances, incorporating the work of others. Students and investigators of these fields are greatly indebted to him for the valuable assistance which was thus provided for them.

In 1913 Eddington was elected, at the age of thirty-one, to the Plumian Professorship of Astronomy at Cambridge, which had become vacant through the death of Sir George Darwin. In the following year, after the death of Sir Robert Ball, he was appointed Director of the Cambridge Observatory, where he resided until his death. Almost at once there commenced a long period of most fruitful activity. In 1916 appeared the first of an important series of papers on the radiative equilibrium of the stars, which broke new ground and completely altered the outlook of astronomers on many problems. In the earlier investigations of the distribution of temperature inside a star by Homer Lane, Ritter, Emden and others, it had been assumed that the transfer of heat within the star was brought about by means of convection currents. The theory of radiative equilibrium assumes that the heat is transferred by radiation, so that the temperature distribution is controlled by the flow of radiation. Convection currents may strive to establish a different distribution, but the transfer of heat by radiation is so much more rapid than by convection that radiative equilibrium must provide a very close approximation to the conditions prevailing in the interior of a star. The concept of radiative equilibrium seems to have been first adopted by Sampson in 1894, but the thermodynamics of radiation was not at that time sufficiently developed for the concept to be satisfactorily worked out. In 1906 Schwarzschild had applied the theory of radiative equilibrium to the Sun's atmosphere. Eddington was the first to apply it to the interior of a star. He derived the famous equation of radiative equilibrium which bears his name, and showed that it became integrable when a simple assumption was made. This led to the polytropic sphere with index $n = 3$, known as Eddington's model. The theory requires an assumption about the mean molecular weight of the stellar material which Eddington at first assumed to be equal to that of iron. It was suggested to him independently by Newall, Jeans and Lindemann that in stellar conditions the atoms would be highly ionized and that the mean molecular weight must be much lower. In the

second paper he therefore adopted a mean molecular weight of 2, which is approximately correct for all elements except hydrogen. He found that the luminosity of a giant star depended mainly on its mass, increasing rapidly with the mass. He pointed out that for the range of stellar masses between about one-tenth and a hundred times the Sun's mass, the radiation and gas pressures were comparable, which appeared to provide an explanation of the comparatively narrow range in observed stellar masses.

Eddington had supposed that the formulæ he had derived were applicable only to gaseous giant stars. In the interiors of stars of the main sequence, with their much higher mean densities, it was expected that there would be an appreciable departure from the perfect gas laws, so that the formulæ would cease to be applicable. On the current theory of evolution, a star began as a giant red star and passed successively through the two branches of the Hertzsprung-Russell diagram. A main sequence star of a given mass should therefore have a lower luminosity than a giant star of the same mass. In 1924 he set out to discover to what extent the dense stars deviated from the luminosities of gaseous stars of the same masses. A careful discussion of all the reliable determinations of stellar masses was made and the unexpected result was obtained that the formulæ of the theory predicted correctly the absolute magnitudes of all ordinary stars, irrespective of whether they were giants or main sequence stars. The explanation was at once suggested by Eddington—that the highly ionized matter in the interior of a star would behave practically like a perfect gas up to very high densities.

This discovery of the correlation between the masses and the luminosities of the stars, applicable equally to the giant and main sequence stars, was a result of outstanding importance. It necessitated a complete revision of currently accepted views of stellar evolution. The two branches of the Hertzsprung-Russell diagram must either represent loci of equilibrium points or, if there was evolution along them, it must be accompanied by appreciable loss of mass. Little was known at that time about atomic nuclear processes, and the alternative possibilities of the source of stellar energy being provided by the annihilation of matter or by the transmutation of hydrogen were discussed.

The white-dwarf stars did not satisfy the mass-luminosity relationship. At the transcendently high densities of these stars an appreciable departure from the perfect gas laws occurred. Eddington came to the revolutionary conclusion that the mean density of 61,000 of the companion of Sirius was not absurd and must be accepted. He pointed out that if this density were correct there should be an Einstein shift of its spectral lines of about 20 km. per sec., which was shortly afterwards confirmed by Adams at Mount Wilson. This provided strong confirmation of the conclusion that in ordinary dwarf stars matter may have the density of platinum and yet behave as a perfect gas, because it is still a long way from the maximum density.

In 1925 Eddington discussed the point-source model of a star. The predicted brightness of a star is decreased by concentrating the source of energy towards the centre; the extreme case is obtained when the concentration is complete, the source of energy being a point-source at the centre of the star. He was able to solve the problem by means of quadratures, and he showed that the influence of the internal density distribution upon the mass-luminosity relation was small. The numerical results obtained emphasized that the general internal conditions determine the surface conditions and not *vice versa*. The latter view, maintained by some investigators, was vigorously opposed by Eddington.

There remained one serious discordance in these investigations which troubled Eddington a great deal. The opacity of the stellar matter, inferred from the mass and luminosity of the star, proved to be ten times greater than that inferred from laboratory data as to absorption of X-rays, coupled with the thermodynamic theory of ionization. Eddington developed a theory of nuclear capture which gave full agreement with the astronomical observations; it was necessarily in conflict with laboratory experiment and was later discarded. Kramers's theory of electron capture, on the other hand, was in

agreement with laboratory experiment; Eddington recognized that the discrepancy could be removed by assuming that the stars contain a large proportion of hydrogen, though he was not at first prepared to accept this explanation. But in 1932, after considering the guillotine factor in stellar opacity, he reconsidered this matter and, proceeding in the reverse direction, determined the hydrogen content for a star of known mass, radius, and luminosity, on the assumption of the validity of Kramers's theory. He pointed out that if stars of the same mass differed widely in their hydrogen content the deviations from the mass-luminosity law would be much wider than observed. For a star with the mass of the Sun the luminosity can range over seven magnitudes according to the proportion of hydrogen.

This series of investigations, with the exception of the last, were collected and discussed in detail in the important work entitled *The Internal Constitution of the Stars*, published in 1926. In spite of the great mass of investigations which have been stimulated in the years that have intervened by the pioneer work of Eddington, the book remains a classic of astronomy, which is invaluable to the student. Eddington's physical insight was so discerning that the main structure remains substantially sound after nearly twenty years.

In this book Eddington gives a digression on the different view-points of the mathematician and the physicist which is worth quoting, because it so exactly illustrates his own attitude towards the problems he discussed:

> "I consider that the chief aim of the physicist in discussing a theoretical problem is to obtain 'insight'—to see which of the numerous factors are particularly concerned in any effect and how they work together to give it. For this purpose a legitimate approximation is not just an unavoidable evil; it is a discernment that certain factors—certain complications of the problem—do not contribute appreciably to the result. We satisfy ourselves that they may be left aside; and the mechanism stands out more clearly, freed from these irrelevancies. This discernment is only a continuation of a task begun by the physicist before the mathematical premises of the problem could be stated; for in any natural problem the actual conditions are of extreme complexity and the first step is to select those which have an essential influence on the result—in short, to get hold of the right end of the stick. The correct use of this insight, whether before or after the mathematical problem has been formulated, is a faculty to be cultivated, not a vicious propensity to be hidden from the public eye. Needless to say the physicist must if challenged be prepared to defend the use of his discernment; but unless the defence involves some subtle point of difficulty it may well be left until the challenge is made.
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> "I suppose that the same kind of insight is useful to the mathematician as a tool; but he is careful to efface the tool marks from his finished products—his proofs. He is content with a rigorous but unilluminating demonstration that certain results follow from his premises, and he does not generally realize that the physicist demands something more than this. For the physicist has always to bear in mind a thousand and one other factors in the natural problem not formulated in the mathematical problem, and it is only by a demonstration which keeps in view the relative importance of the contributing causes that he can see whether he has been justified in neglecting these. As regards rigour, the physicist may well take risks in a mathematical deduction if these are no greater than the risks incurred in the mathematical formulation. As regards accuracy, the retention of absurdly minute terms in a physical equation is as clumsy in his eyes as the use of an extravagant number of decimal places in arithmetical computation.
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> "Having said this much on the one side we may turn to appreciate the luxury of a mathematical proof. If the results obtained do not agree with observation the fault must assuredly lie with the precision assumed. The mathematician's power of narrowing down the possibilities supplements the physicist's power of

picking out the probabilities. If space were unlimited we might try to duplicate investigations where necessary so as to satisfy both parties. But if one investigation must suffice, I do not think we should usually give way to the mathematician. Cases could be cited where physicists have been led astray through inattention to mathematical rigour; but these are rare compared with the mathematician's misadventures through lack of physical insight.

"The point to remember is that when we *prove* a result without understanding it—when it drops unforeseen out of a maze of mathematical formulæ—we have no grounds for hoping that it will apply except when the mathematical premises are rigorously fulfilled—that is to say, never, unless we happen to be dealing with something like æther to which 'perfection' can reasonably be attributed. But when we obtain by mathematical analysis an *understanding* of a result—when we discern which of the conditions are essentially contributing to it and which are relatively unimportant—we have obtained knowledge adapted to the fluid premises of a natural physical problem.

"I think the idea that the purpose of study is to arrive at a string of proofs of propositions is a little overdone even in pure mathematics. Our purpose in studying the physical world includes much that is not comprised in so narrow an ideal. We might indeed say that whereas for the mathematician insight is one of the tools and proof the finished product, for the physicist proof is one of the tools and insight the finished product. The tool must not usurp the place of the product even though we fully recognize that disastrous results may occur when the tool is badly handled".

The Internal Constitution of the Stars contained the results of three other related investigations. In 1918–19 Eddington had published two important papers dealing with the problem of the Cepheid variable stars, on the hypothesis that their light variations were caused by periodic pulsations. He was able to account for the period-luminosity relationship obeyed by these stars, which had been found by Miss Leavitt at Harvard from the study of Cepheid variables in the Magellanic Clouds. These papers have formed the basis of all later work on the subject. Eddington returned to the subject again in 1941 in an attempt to account for the phase retardation of approximately one-quarter period between the flow of heat in the main part of the interior of the star and the outflow of heat from the surface. He pointed out that the period is sensitive to changes of density and the luminosity to changes of mass; the period-luminosity relationship is, consequently, in effect a mass-density relation. This implies that for any given mass there must be a narrow range of density within which the star is pulsatorily unstable. The most probable transient modification was a sharp drop in the ratio of the specific heats when the predominant element was at the mid-stage of an ionization. This possibility he had previously considered but the predominant element was then presumed to be a heavy element, such as iron, and the assumption was found to lead to results not in accordance with observation. But the substitution of hydrogen as the most predominant element brings the critical region from the deep interior to near the surface. In the convective layer of the star, however, the equilibrium calculations of ionization and excitation break down. These papers were criticized by M. Schwarzschild, who showed that the deviation from ionization equilibrium in the hydrogen convection zone was less than Eddington had supposed. In reply, Eddington maintained that a simple explanation of the quarter-phase retardation could be provided if it were supposed that the convection zone was much deeper than had been previously assumed and that there is a large difference in the state of ionization of the upward and downward streams.

The second investigation, in 1926, was concerned with the reflection effect in eclipsing variables. If the components of an eclipsing variable are sufficiently close, the reflection by the faint star of the light of the bright star causes the hemispheres turned towards and away from the bright component to be unequal in brightness. This effect, in

combination with the spherical distortion of the two stars, gives rise to variations in light between eclipses.

Eddington's discussion was supplemented, at his suggestion, by Milne shortly afterwards, who inquired into the problem of the distribution of the reflected radiation in direction, *i.e.* of the law of darkening of the disk for reflected radiation. The discussions by Eddington and Milne have satisfactorily solved this problem.

The third investigation dealt with diffuse matter in interstellar space, which had formed the subject of the Bakerian Lecture of the Royal Society in 1926. This was an important contribution to the understanding of the nature of the stellar clouds. He found that ionization and capture form the main processes of interchange between radiant energy and atomic kinetic energy in diffuse gas, and that this tended to raise the temperature to the level of the effective temperatures of the stars, independently of the dilution of radiation. The relative abundance of sodium to calcium was found to be very much greater than on the Earth; the tremendous preponderance of hydrogen over all other elements was not realized at that time, and Struve later showed that the discordance was much reduced when it was assumed that hydrogen supplied the overwhelming majority of the free electrons. Eddington concluded that the stationary sodium and calcium lines in the spectra of early-type stars were produced by absorption by the interstellar cloud. He pointed out that electron scattering does not cause reddening, so that Shapley's conclusion that interstellar space is nearly transparent because there is no reddening of distant clusters was invalid; the dimming of distant stars by interstellar matter could not be accounted for unless it is assumed that interstellar space contains non-gaseous (meteoric) matter. This conclusion has since been amply confirmed.

Stars and Atoms, published in 1927, gave a fascinating and graphic description of the investigations of stellar interiors in a form intelligible to the general reader. Eddington's popular writings did great service to science in expounding to the layman the meaning and implications of the new developments in astronomy and physics. They were written in a clear and elegant prose, with many graphic analogies, and had a charm and individuality of their own. Many passages could be quoted in illustration, but one from *Stars and Atoms* picturing the conditions inside a star must suffice:

> "We can now form some kind of picture of the inside of a star—a hurly-burly of atoms, electrons and æther-waves. Dishevelled atoms tear along at a hundred miles a second, their normal array of electrons being torn from them in the scrimmage. The lost electrons are speeding a hundred times faster to find new resting places. Let us follow the progress of one of them. There is almost a collision as an electron approaches an atomic nucleus, but putting on speed it sweeps round in a sharp curve. Sometimes there is a side-slip at the curve, but the electron goes on with increased or reduced energy. After a thousand narrow shaves, all happening within a thousand-millionth of a second, the hectic career is ended by a worse side-slip than usual. The electron is fairly caught and attached to an atom. But barely has it taken up its place when an X-ray bursts into the atom. Sucking up the energy of the ray, the electron darts off again on its next adventure.
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> "I am afraid the knockabout comedy of modern atomic physics is not very tender towards our æsthetic ideals. The stately drama of stellar evolution turns out to be more like the hair-breadth escapades on the films. The music of the spheres has almost a suggestion of—jazz.
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> "And what is the result of all this bustle? Very little. The atoms and electrons for all their hurry never get anywhere: they only change places. The æther-waves are the only part of the population which accomplish anything permanent. Although apparently darting in all directions indiscriminately, they do on the average make a slow progress outwards. There is no outward progress of the atoms and electrons; gravitation sees to that. But slowly the encaged æther-waves leak outwards as through a sieve. An æther-wave hurries

from one atom to another, forwards, backwards, now absorbed, now flung out again in a new direction, losing its identity, but living again in its successor. With any luck it will in no unduly long time (ten thousand to ten million years, according to the mass of the star) find itself near the boundary. It changes at the lower temperature from X-rays to light-rays, being altered a little at each re-birth. At last it is so near the boundary that it can dart outside and travel forward in peace for a few hundred years. Perhaps it may in the end reach some distant world where an astronomer lies in wait to trap it in his telescope and extort from it the secrets of its birthplace".

Eddington was a man of wide reading, with a retentive memory for the apposite quotation. The chapters of several of his books are headed by quotations and in his popular writings quotations are frequent. He drew upon an astonishingly wide range of authors and his quotations are always most apt. Quotations from Shakespeare are frequent; one in the Preface to *The Internal Constitution of the Stars* may be recalled:

"The reader will judge for himself whether solid progress has been made. He may, like Shakespeare, take a view less optimistic than my own—

> The heaven's glorious Sun
> That will not be deep-searched with saucy looks;

but I hope he will not be so unkind as to continue the quotation—

> Small have continual plodders ever won
> Save base authority from others' books".

In his days at Greenwich, Eddington had been a member of a small private Society, called "The Elizabethans", which was closely connected with the Observatory. The members met monthly during the winter months in each other's homes to read one of Shakespeare's plays, the various characters being allotted to different members.

Concurrently with the investigation of stellar interiors, Eddington had also been occupied with the theory of generalized relativity. The First World War prevented the transmission of Einstein's papers to this country for some time after his discovery of the theory in 1915. Eddington had received a copy from de Sitter in 1917 and was the first Englishman to appreciate its importance and to accept it unreservedly. His *Report on the Relativity Theory of Gravitation*, prepared for the Physical Society in 1918, provided the first account of the new theory in the English language and did valuable service in bringing the theory to the notice of British men of science. Many were converted to it; but many others, because of its revolutionary conceptions and the employment in its mathematical development of the tensor calculus, with which physicists and applied mathematicians were not generally familiar, were inclined to suspend judgment. The theory had accounted for the unexplained motion of the perihelion of Mercury, but further observational confirmation was needed to convince the sceptics. It was pointed out by Sir Frank Dyson that the total eclipse of the Sun on 1919 May 29 would provide a particularly favourable opportunity for testing Einstein's prediction of the amount of the deflection of rays of light by the Sun. It was decided to proceed with the necessary preparations at Greenwich for two expeditions to Brazil and the island of Principe, in the hope that the war would come to an end in time for the expeditions to set out. Davidson and Crommelin were to be the members of one party, to make observations in Brazil, and because many astronomers were in the Forces or engaged on war work, Eddington agreed to lead the other party, taking with him Cottingham, the horologist, to make observations in Principe. The war fortunately ended in time for the expeditions to set out and both parties made successful observations. At Principe clouds interfered with the observations so that only two plates showed sufficient stars to enable a determination of the deflection to be made: the result from these plates was $1''{\cdot}61 \pm 0''{\cdot}30$. The conclusion from the results of the two expeditions was that Einstein's

prediction of the amount of the deflection was confirmed, and greatly helped to secure a wide acceptance of the theory. Before the expeditions set out it was suggested that three results were possible: the deflection might prove to be in accordance with Einstein's prediction; it might be half this amount, as would be expected on Newtonian theory because light-waves carry momentum; or it might be nil. Eddington had so unreservedly accepted the theory that he was convinced that satisfactory observations could lead only to the first conclusion; in discussing these three possibilities, he remarked that the most difficult result to account for would be the second.

It may be mentioned here that the most satisfactory confirmation of Einstein's third prediction, the displacement of spectral lines, has since been provided by the measurement of the displacement of the spectral lines of the companion of Sirius, referred to above, which was closely tied up with Eddington's own work.

In *Space, Time and Gravitation* (1920) Eddington gave a non-mathematical account of the theory, to which he prefixed the very apposite quotation from "Paradise Lost":

> Perhaps to move
> His laughter at their quaint opinions wide
> Hereafter, when they come to model heaven
> And calculate the stars: how they will wield
> The mighty frame: how build, unbuild, contrive
> To save appearance.

In 1923 he followed this with *The Mathematical Theory of Relativity*, which included an account of his own original investigations. The most notable of these, published in 1921 in *Proc. Roy. Soc.*, introduced a new generalization of geometry, founded on the idea of parallel-transport, which he put forward not as the actual geometry of space and time but as the geometry of world-structure, the common basis of space and time and matter. Quite apart from the physical applications which were most prominent in Eddington's mind, this work has proved of fundamental significance for the purely mathematical theories of non-Riemannian geometry.

He himself attached great importance to an interpretation of General Relativity which he set forth in two short papers in the *Phil. Mag.* of 1921 November and 1922 January. Starting from the principle that there is no such thing as absolute length (so that to say a length is constant merely means that its ratio to some other length is constant) he inferred that what we call a metre at any place and in any direction is always a constant fraction of the radius of curvature of space-time associated with that place and direction. Hence the Riemann curvature at a point of space-time must be the same for all orientations, and must be the same for all points of space-time. But the conditions for this are

$$K_{pq}=\lambda g_{pq} \qquad (p, q=0, 1, 2, 3),$$

where K_{pq} is the contracted curvature-tensor, g_{pq} is the metrical tensor and λ is a constant: and these are no other than Einstein's equations for the gravitational field in empty space. Thus Einstein's law asserts the homogeneity and isotropy of space-time as regards Riemann curvature; but the mystery of the homogeneity and isotropy disappear when we realize that it is not intrinsic in the external world but in the measurements we make of the world: the law simply expresses the fact that our survey of the world is made by instruments which are themselves part of the world. With this new insight came the conviction, which dominated the rest of his life, that the true foundation of physics must be in epistemology—the theory of knowledge.

The years from 1928 onwards were occupied chiefly in applying the epistemological principles to the creation of a new and highly original fundamental theory, by means of which he succeeded in deriving theoretically the exact numerical values of all those constants of nature which are pure numbers. There has been considerable misunderstanding about the character of this series of investigations; it has sometimes been

supposed (erroneously) that Eddington claimed to have derived the whole of physics, or a large part of it, by pure ratiocination, without depending in any way on the results of observation and experiment. Such an idea is refuted at once by an examination of the papers themselves. The position may be illustrated by reference to the history of an older problem. The ancient Egyptians were acquainted with the fact that the ratio of the area of a circle to the square on its radius was independent of the size of the circle: and for this number, which we denote by π, they found, by actual measurement, the value $\frac{2}{8}\frac{5}{1}\frac{6}{}(=3{\cdot}16\ldots)$. In the third century before Christ, Archimedes showed that the number can be found to any desired degree of accuracy by pure theory, without the necessity for making measurements. For this purpose he assumed the axioms and propositions of geometry as they had been set forth in the preceding generation by Euclid: so that what Archimedes did was to assume the *qualitative* part of geometry and to deduce a *quantitative* aspect of it, namely the number π.

Now Eddington is simply the modern Archimedes. He regarded himself as at liberty to borrow anything in *qualitative* physics—he did in fact assume the identity of mass and energy, the theory of the energy-tensor and the interpretation of its elements, the Pauli exclusion principle and other propositions of the most advanced physical theory—but he did *not* assume any *number* determined *empirically*: and he deduced the *quantitative* propositions of physics, *i.e.* the exact values of the pure numbers that are constants of nature—the numbers that are analogous to the number π in geometry.

One can imagine the protests of those contemporaries of Archimedes who had been accustomed to find π by measuring circles, when he took the bread out of their mouths by his mathematical evaluation: and a similar outcry was raised by certain experimental physicists against Eddington, who, it must be admitted, sometimes played into their hands by using language which was liable to be misunderstood. For instance, he obtained for "the number of particles in the universe" a value which, his critics complained, could never be checked by observation; actually a study of his papers shows that the number N thus referred to is carefully defined and has a value which can be determined independently of Eddington's work by a combination of orthodox relativity-theory and astronomical measurements. The definition depends on the concept of an *Einstein world*; that is, a uniformly curved space filled with matter of uniform density in which the mutual gravitational attraction of its particles is exactly balanced by their mutual repulsion due to the cosmical term in General Relativity; N is then simply the number of particles in an Einstein world formed of hydrogen.

Eddington's original method (1931) of finding N theoretically was heuristic in character and has been superseded by his later work, but it is of great interest as revealing the psychological process of discovery. The idea was that in the ordinary Dirac wave-equation for an electron moving in the electrostatic field due to a fixed electron, the term which involves the mass of the electron is really due to the existence of all the other particles in the world; whence he showed that it must have the form $\sqrt{N}/R$, where R is the radius of the Einstein world. Thus he obtained the equation

$$\sqrt{N}/R=(mc^2)/e^2,$$

where m is the mass and e the charge of an electron, and c is the velocity of light. Combining this with the equation

$$\kappa\frac{Nm_p}{c^2}=\tfrac{1}{2}\pi R$$

(where κ is the Newtonian constant of gravitation and m_p the mass of a proton), which is derived from the theory of the Einstein world, it is clear that N and R can both be determined. Substituting the value of R in the theoretical expression for the rate of cosmical recession, Eddington obtained for the latter quantity the value 527·8 km. per sec. per megaparsec., which agreed fairly well with the observed recession. Later he

found more accurate ways of calculating the recession from the constants of atomic physics.

A connected account of the series of investigations in which the theory had been developed from 1928 was given in 1936 in his book *Relativity Theory of Protons and Electrons*: it was based almost wholly on what he called the "spin extension" of relativity theory. After this he approached the same problems by a different method, which he called the "statistical extension" of relativity theory: an account of this was given in his Dublin lectures, *The Combination of Relativity Theory and Quantum Theory*, in 1943. At the time of his death he was engaged in writing a book, the completed portion of which is now in course of publication, in which both methods were combined.

The qualitative physical theory which Eddington assumed as the basis of his researches was not in all respects identical with that most widely accepted at the present time; for instance, he refused to believe that the meson observed in cosmic rays is identical with the theoretical meson introduced by Yukawa to explain the forces between the heavy particles in the nucleus. His theory of the nucleus, again, was distinctive: from general principles he derived two different types of binding between a proton and an electron, one the ordinary binding by a Coulomb force, and the other a "co-spin" binding which can unite the proton and electron into a neutron: the nucleus he conceived not as an aggregate of protons and neutrons, but as an aggregate of protons and electrons, the latter being united by co-spin binding not to individual protons, but to the whole aggregate of them.

He went further than any other investigators in getting rid of the old ideas of space, time and particles as the basis of physics: thus in his work on the hydrogen atom, instead of picturing it as an electron circulating round a proton like a planet round the Sun, he devised a totally different representation, analysing it into an "extracule" and "intracule", which correspond roughly to the symmetric and skew parts of the wave function.

Just as Newton's discovery of gravitation was founded on recognizing that the force causing an apple to fall from a tree was identical with the force restraining the Moon in her orbit, and just as Einstein's discovery of general relativity was founded on recognizing that the gravitational properties of mass are identical with its inertial properties, so Eddington's theory is founded on a belief in the essential identity of forces which in current physics are regarded as distinct—*e.g.* he identifies gravitation with the exclusion principle, and Coulomb-interaction with interchange-energy.

In formulating the quantitative results of the theory, it is to be remembered that experimental measures are expressed in the three traditional units gram-centimetre-second, which have no relation to any theory, and it was therefore necessary for Eddington to select three measured quantities to be used as conversion constants: he chose the velocity of light, the Rydberg constant and the Faraday constant. Combining these with his theoretical determinations of the purely numerical constants of nature, he obtained values for the charge of the electron, the Planck constant, the constant of gravitation, the speed of recession of the galaxies, the forces between the protons in the nucleus, the masses of the electron, the proton, the neutron, and the cosmic-ray meson, the mass-defects of deuterium and helium, the separation-constant of isobaric doublets, the lifetime of the cosmic-ray meson, and the magnetic moments of the hydrogen atom and the neutron. In practically all cases the values so found agree with the observed values within the margin of observational error. It was not without justification that in his latest writings, in which his work is presented as a unified whole, he adopted for it the name *Fundamental Theory*.

Eddington's views on general philosophical questions related to physical science were given in *The Nature of the Physical World* (1928), being the Gifford Lectures for 1927; *New Pathways in Science* (1935), being the Messenger Lectures at Cornell for 1934; and the *Philosophy of Physical Science*, being the Tarner lectures at Trinity

College, Cambridge, in 1938. In these books he dealt with the new developments in science—the theory of relativity, quantum theory, the principle of indeterminacy, the expansion of the universe, etc.—and with their effect on philosophical thought. The books were essentially concerned with the question, What kind of knowledge does science give us? He showed that in dealing with the universe, science is confined to investigating its structure; it can tell us nothing of the nature of that which possesses that structure. It was not so much the particular form that scientific theories have now taken that is important, for they may in time give way to some fuller realization of the world, as the movement of thought behind them changes. Whatever changes may come, it will never be possible to go back to the old outlook. Mention may also be made of a small popular book, *The Expanding Universe* (1933), which gave an account of the phenomena to be expected in a finite expanding spherical universe, of the type first suggested by Einstein and later developed by the Abbé Lemaître. These lucid books did more than any other books to make the intelligent layman aware of the new trends in science and of their philosophical implications. They did not escape considerable criticism from philosophers, but Eddington was always a fighter for his ideas and was a redoubtable opponent in argument: he hit back vigorously. The philosophers, for the most part, lacked the scientific knowledge to appreciate his point of view. There is little doubt that the philosophical implications of recent developments in scientific thought will compel philosophers to reconsider many of the views that have been held in the past.

Eddington was elected a Fellow of the Royal Society in 1914 and was awarded its Royal Medal in 1928. He was elected a Fellow of the Royal Astronomical Society in 1906, was its President during 1921–23, a period which included its centenary celebrations, and its Foreign Secretary from 1933; he was awarded its Gold Medal in 1924. He was awarded the Bruce Gold Medal of the Astronomical Society of the Pacific in 1924. He was President of the Physical Society during 1930–32. He received honorary doctorates from twelve universities, and was honorary member, foreign member or foreign associate of many learned societies in Europe and America. He was created a Knight Bachelor in 1930 and received the Order of Merit in 1938. He had friends in many parts of the world, for he had travelled and lectured widely, attending overseas meetings of the British Association, Congresses of the International Astronomical Union, and paying frequent visits to the Continent and to America. He was a true ambassador of science and contributed greatly to the cause of international co-operation in science. At the last General Assembly of the International Astronomical Union in 1938 he was elected President; his guidance at a time when the Union will have complex and difficult problems to face will be sadly missed.

Though Eddington was primarily an astronomer, much of his work was intimately bound up with the most modern developments in physics. In these days of specialization in science it is given to few to have so wide a range of interests and to make contributions of outstanding merit in such diverse fields as he did. He combined to a unique degree an appreciation of the significance of new developments with great powers of mathematical analysis and keen physical insight. A gifted expositor of the newest trends in physics, he was able to describe the most abstruse theories in clear and simple language. His death on 1944 November 22, at the comparatively early age of sixty-one, was a calamity for science; he was still in the zenith of his intellectual powers and his work was not finished. Many in Great Britain and abroad mourn the passing of a friend; their sense of loss is shared by many others in all parts of the world who have admired his achievements and have received instruction and stimulus from his writings. But his work will endure and his name will be enrolled amongst the greatest men of science whom this country has produced.

H. SPENCER JONES.
E. T. WHITTAKER.

RALPH HOWARD FOWLER, Plummer Professor of Mathematical Physics at Cambridge, died on 1944 July 28, at the age of fifty-five, as the result of an illness which first attacked him in 1938. Though he struggled valiantly, too valiantly, against it, its ravages prematurely aged him and he was carried off at what might have been the height of his powers. Pure mathematician, applied mathematician in such differing branches as ballistics and quantum theory, statistical mechanics and physical chemistry, proficient at cricket and more than proficient at golf, a man of affairs as well as a pure scientist, and a faithful servant to more than one government department, he was distinguished for the versatility and quickness of his mind, for his power of immediately coming to close grips with any problem presented to him, for his rapidity of decision and his sagacity of judgment, and above all for the part he played in developing the school of mathematical physics at Cambridge. Fowler was a big man, both physically and in the world of science; he was a hard hitter, in every sense of that phrase; he was a man of winning charm, who inspired devoted friendships; and his friends in both official and non-official circles had foreseen a future for him even more full than the career which was so tragically closed.

Ralph Howard Fowler was born on 1889 January 17, at Fedsden, Roydon, Essex, the eldest son of Howard and Ena Fowler. His father, Howard Fowler, was the second son of William Fowler, of Moor Hall, Harlow, Essex; he had been educated at Clifton and at New College, Oxford, where he was an exhibitioner, and he had played cricket for Oxford University for three years, and Rugby football for three or four seasons, also representing England at Rugby. Ralph evidently inherited his general athletic ability from his father.

In 1902, at the age of thirteen and a half, he was elected to a scholarship at Winchester. He remained there till 1908. He became Prefect of Hall (as the Head of the School is called), and played in the cricket match against Eton in his last year.

In 1906 December, Ralph was elected to a Major Scholarship at Trinity College, Cambridge, and he went up to Trinity in the Michaelmas Term of 1908. Here he read mathematics, taking a first class in the Mathematical Tripos, Part I, in 1909, and becoming a wrangler in Part II in 1911, with a mark of distinction in Schedule B. He became B.A. in 1911, M.A. in 1915. He was awarded a Rayleigh Prize for Mathematics in 1913.

He obtained his blue for golf (or, to be accurate, in those days a half-blue) by playing in the Cambridge four against Oxford in 1912, having also played in many matches in 1911.

After taking his degree he began to research on problems of pure mathematics. He was attracted to problems of the behaviour of solutions of second-order differential equations, namely of the form "near infinity" of real, continuous solutions of such equations. An early paper in the *Quarterly Journal of Mathematics*, edited by J. W. L. Glaisher, dealt with cubic transformations of Riemann's *P*-function, and seems to have been inspired by work of E. W. Barnes, the present Bishop of Birmingham, whose lectures on differential equations Fowler must have attended as an undergraduate. Further papers appeared, in the *Quarterly Journal* and in the *Proceedings of the London Mathematical Society*, on the classification of the asymptotic behaviour of the solutions; and there was a paper on the set of points $(\lambda_n\theta)$, where θ is an irrational, inspired by work of Hardy and Littlewood. Fowler was subsequently to make great use of his early experience in these fields, firstly in work done in collaboration with C. N. H. Lock, also on approximate solutions of certain differentional equations, secondly in work done in 1930 in connexion with investigations on stellar structure by the present writer, who was studying solutions of Emden's differential equation

$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right) = -\theta^n.$$

The origin of this work is perhaps worth relating in detail. Eddington had shown

that the equilibrium of a gaseous star was given by the above equation with $n=3$, and had deduced, *from equilibrium considerations only*, a formula for the luminosity of the star in terms of the mass. I was puzzled as to what happened when the rate of generation of energy did not have this particular value. Clearly, if the star were generating a great deal too much energy, it would blow up by radiation pressure. What happened when it generated too little, or only slightly too much? The answer came into my mind as a sudden intuition: the star must cease to be gaseous and *Emden's differential equation must have other solutions*. I at once wrote to N. Fairclough, asking him to undertake some new numerical integrations with non-Emden boundary conditions, integrating from the outside inwards; and discussed the matter with T. G. Cowling. The results of both these investigators arrived at the same time and gave the hint to the hitherto incompletely known behaviour of the non-Emden solutions in their dependence on boundary conditions. I communicated Fairclough's numerical quadratures to Fowler, who immediately saw their theoretical significance. They gave him the clue which had been missing in his post-graduate researches, and he at once devised a beautiful and at the same time rigorous method of handling and classifying the solutions of Emden's equation for different exponents n and for all types of boundary conditions. The results were published in the *Monthly Notices*, and had a considerable influence in helping to classify the possible configurations of gaseous and partly gaseous stellar configurations. Later Fowler extended the work to more general equations, and published the resulting theorems in the *Quarterly Journal* in its revived Oxford form.

To return to his career: he was elected, as a result of this work in pure mathematics, to a Trinity Fellowship in 1914 October. By then the first German war had broken out, and Fowler obtained a commission in the Royal Marine Artillery.

Before passing on to Fowler's war career, I may refer to his remaining contribution to pure mathematics, his tract on "The elementary differential geometry of plane curves", which was published as a *Cambridge Tract in Mathematics* (No. 20) in 1920, and reached a second edition in 1929. This put into modern rigorous form ground usually covered in French *cours d'analyse* in their chapters on geometry, and contained some original work in what might be thought to be a well-trodden field.

Fowler took part in the ill-fated Gallipoli campaign as a gunner officer in the Marines, and was badly wounded in the shoulder. Whilst he was convalescing in 1916 (he was then a First Lieutenant, R.M.A.), A. V. Hill, then a Captain in the Cambridgeshires, was inventing, in conjunction with Horace Darwin, of the Cambridge Scientific Instrument Company, the instrument later known as the Darwin-Hill Mirror Position Finder—an instrument originally designed to record the flight of aeroplanes. Hill proposed to Fowler that the two of them should combine to test this instrument in the field, and thus began R. H. Fowler's interest in mathematical physics. This association with A. V. Hill was indirectly to alter the whole course of Fowler's interests and studies.

Hill, Fowler, and myself were in theory the servants of the Munitions Inventions Department of the then Ministry of Munitions, but Hill saw to it that he had largely a free hand, not greatly impeded by bureaucratic interference. We were soon joined at Northolt by W. Hartree and A. C. Hawkins. During this Northolt period, Hill and Fowler wrote a famous secret pamphlet, "M.I.D. 2", on the working and errors of the mirror position finder. The instrument soon came to be used for testing readings of height finders, and Hill's party moved to the National Physical Laboratory at Teddington sometime in 1916 May. There they were joined by W. Hartree's son, D. R. Hartree, and H. W. Richmond.

It now occurred to Hill that the principal rôle of the instrument would be to make accurate observations on high-angle shell-bursts produced by firing anti-aircraft guns. J. E. Littlewood, then a Second Lieutenant in the gunners attached to the Ballistic Office at Woolwich, had devised a rapid and powerful method of calculating high-angle trajectories avoiding the painfully long process of "small arc" integration, by determining first the time-height relation for "vertical fire" and using this, combined with a use of

Siacci-formulæ for fire on the flat, to determine trajectories at any angle. But no one knew whether projectiles really followed Littlewood's trajectories or not. Hill induced the then Ordnance Committee to let him take his mirrors and party to Gorleston-on-Sea, to observe some range-table firings from a 6-inch A.A. gun mounted on a monitor on the river there. After some delays due to unsatisfactory weather, adequate observations were obtained, and to the astonishment and joy of all concerned, the observed positions of the shell-bursts fell exactly on Littlewood's trajectories, at the correct time-markings, within the very small errors of observation.

Hill next persuaded the Ordnance Committee to stage extensive trials of various calibres of A.A. guns at Eastney, Portsmouth, under the general supervision of the Experimental Department of H.M.S. *Excellent*; and the party moved in 1916 August to H.M.S. *Excellent's* headquarters on Whale Island, where they remained until the close of the war. The gun-trials became more comprehensive, including fuze-trials, and a larger staff was recruited. There came to join Hill and Fowler in due course the mathematicians G. T. Bennett, T. L. Wren, R. A. Herman, C. E. Haselfoot, D. R. Hartree's brother, C. W. Hartree, J. G. Crowther, W. E. H. Berwick, W. R. Dean, S. Pollard, the physicist C. Mayes, and many others. The party was known as the Anti-Aircraft Experimental Section of the M.I.D., and Fowler became its Assistant Director, resident at Portsmouth, whilst Hill, as Director, though frequently visiting Portsmouth, made contacts in London with service needs. Hill became a brevet Major, Fowler a Captain R.M.A. The two fitted like hand and glove. Hill was the inspirer of most of the researches that were conducted, whilst Fowler executed them in the field. It was a most friendly community—sometimes bullied by Fowler (though he always assuaged its feelings afterwards), and then released from its tension by a visit from Hill. But what is significant to record in a short biography of Fowler's is the important scientific influence which Hill had on him, and he in turn on the other members of the section. At directing research, both were superb; to behold the way they set about a new problem, often in a new terrain with new material, to see the way they made inferences and came to conclusions and sound judgments and to take part in it all, was far better training than most universities can offer to aspirants in research.

After the war proper was over in 1918, Fowler, with the aid of E. G. Gallop, C. N. H. Lock and H. W. Richmond, whilst still connected with Portsmouth, designed an elaborate series of experiments on firing projectiles through "jump cards", and determining the spatial orientation of the projectile, as it passed through them, from the holes it made; the object was to deduce the areodynamic forces and couples (apart from direct air-resistance) on the projectile as it progressed and spun. The results were eventually published in two papers in the *Philosophical Transactions of the Royal Society*, and by-products of them elsewhere. The *Philosophical Transactions* papers became classical, and have had a marked influence on research in ballistics during this present war, both here and in Canada and the U.S.A.

Another piece of war-time research resulted in a joint paper (with the present writer) in the *Proceedings of the Royal Society*, on "Siren harmonics and a pure-tone siren". It was always tremendous "fun" collaborating with Fowler. Usually it was not he (to be quite just) who produced the first original idea; but he tossed it back at lightning speed, and you had to be very agile to field it properly. He had a power of throwing himself unrestrainedly and wholeheartedly into other people's interests which is rarely exhibited; once a thing had been expounded to him and been subjected to his searching cross-examination, he could argue on level terms about it with the leading experts on it, and usually contribute to the discussion some material consideration that they had overlooked. His presence always helped one to see what was the really important aspect of the matter under consideration, and one came away refreshed and with new heart. He was the ideal director of a research institution—as was to be recognized later.

For his work in A.A. research, Fowler was awarded the O.B.E.

In 1919 April he relinquished his commission and resumed residence at Trinity, Cambridge, as a Fellow. He did not, however, cease his connexion with ballistics, for some time later he was made an Associate Member of the re-named Ordnance Board, and the war of 1939 found him again in that capacity.

Once back in Cambridge he plunged into the mathematical life of the place. As remarked, his first self-imposed task was to prepare for publication his material on plane curves. That done, he began to study the newer problems of mathematical physics. These had begun to attract him before he left Portsmouth, for I owe to Fowler my first acquaintance with Jeans' *Dynamical Theory of Gases* and Eddington's Physical Society *Report* on Einstein's general relativity. Though now over thirty years of age, Fowler had the eager mind of a learner, and together we attended E. Cunningham's 9 a.m. lectures on special relativity, and other lectures. But the great influence in his life was now Rutherford, who had returned to Cambridge as Cavendish Professor in 1919. A wonderful friendship sprang up between the two, and it extended to all Rutherford's pupils and co-workers; I say *wonderful* because *a priori* it was rather unlikely that there should exist a strong sympathy between Rutherford, with his depth and search for simplicity and his impatience with abstract mathematical theory, and Fowler, with his breadth and search for generality and his insistence on mathematical rigour. But Rutherford's robust and rugged genius appealed to Fowler, and Fowler's amazing versatility and power of becoming absorbed in problems put to him by others appealed to Rutherford.

Fowler was appointed a College Lecturer in Mathematics at Trinity in 1920. He was soon working on quantum problems, and an early paper in the *Proceedings of the Royal Society* applied an extension of Fourier's integral theorem to quanta.

Then again Fowler became friendly with F. W. Aston, at the time the latter developed his mass spectrograph, and he collaborated with him in a mathematical attack on the problems of focusing beams of charged particles presented by this instrument. He also published in the *Philosophical Magazine* a paper on the classical kinetic theory of gases.

In 1921 Fowler married Eileen, only daughter of Sir Ernest and Lady Rutherford. They had four children. Eileen died shortly after the birth of the fourth, in 1930 December. After her death the children were brought up, along with her own children, by Mrs. Phyllida Cook, most devotedly, and the two households dwelt together in Cromwell House, Trumpington, where the Hartrees had at one time lived.

Up till now Fowler had been, as it were, looking round for problems that were worthy of him. He now (1922) began his serious life-work, by collaborating with C. G. Darwin in papers on the partition of energy, published in the *Philosophical Magazine* and in the *Proceedings of the Cambridge Philosophical Society*. These were inspired by some work by Ehrenfest and Trkal on statistical mechanics. Previously writers had concentrated on evaluating the *most probable* state of an assembly of similar systems interacting with one another. Darwin and Fowler replaced this by the direct calculation of the *average* state of the assembly, determined according to the calculus of probabilities, and they calculated also the magnitude of the *fluctuations* from the average state. They replaced also the customary use of Stirling's Theorem in approximating to factorials by an exact expression in terms of a contour integral, which they evaluated by the method of steepest descents. Appealing to Bohr's Correspondence Principle and Ehrenfest's Adiabatic Hypothesis, they assigned equal *a priori* "weight" to each permissible state in each quantized degree of freedom. They constructed "partition functions" of a variable z, namely the function $f(z)$ equal to $\Sigma p_r z^{\epsilon_r}$, where ϵ_r is the energy of a state r, of a *priori* weight p_r, the partition function for N such similar systems being $[f(z)]^N$. A certain parameter θ which turned up in the subsequent analysis was shown by comparison with thermodynamics to be connected with the absolute temperature T by the relation $\theta = e^{-1/kT}$, k being identified as Boltzmann's constant. The authors began by applying this method to the simplest possible systems—Planck vibrators—and passed to molecules in

space, making the transition to classical mechanics by passing from sums to integrals. They showed that their partition function was analogous to the *Zustandsumme* of Planck, $\Psi = S - E/T$, where S is the entropy and E the energy. They applied the method also to radiation in an enclosure, and derived Planck's Law; and to the internal energy of a crystal.

More particularly, Fowler alone applied their method to assemblies in dissociative equilibrium, both to chemical dissociation and the high-temperature dissociation of atoms at low pressures into ions and electrons. Those were the early days of the theory of high-temperature ionization: out of S. Chapman's and F. A. Lindemann's controversy about the origin of magnetic storms had come the first suggestion, by Lindemann, of the natural ionization of a gas, and independently M. N. Saha had published his celebrated ionization theory of the high level chromosphere and the stellar spectral sequence. Theoretical physicists were still a little sceptical about the application of the methods of physical chemistry—the Nernst heat theorem and the van't Hoff reaction isotherm and isochore—to the separation of electrons from atoms; indeed, it was only after the acceptance of the Bohr theory of spectra and atomic constitution that such progress became possible at all. There was accordingly a great field open for the formulæ and calculations to be justified by the methods of statistical mechanics, and Fowler jumped in, with his mastery of his new technique, and filled the lacuna. He effectively established the validity of the dissociation formula for high-temperature ionization. This was in 1922–1923.

Early in 1923 Fowler and I published in the *Monthly Notices* a joint paper entitled "The intensities of absorption lines in stellar spectra, and the temperatures and pressures in the reversing layers of stars", which had considerable influence in astrophysical theory. For example, it influenced all the early work of Miss Cecilia H. Payne at Harvard. As I have often been asked what were our respective shares in this paper, I propose to describe its genesis.

As I had written on the application of Saha's ionization theory to stellar spectra, showing that the total free-electron pressure had to be taken into account, and as Fowler had just established the ionization formula rigorously, and as there were clearly going to be further applications, we decided to collaborate. Saha had concentrated on the marginal appearances and disappearances of absorption lines in the stellar sequence, assuming an order of magnitude for the pressure in a stellar atmosphere and calculating the temperature where increasing ionization, for example, inhibited further absorption of the line in question owing to the loss of the series electron. As Fowler and I were one day discussing this, it suddenly occurred to me that the *maximum* in the intensity of the Balmer lines of hydrogen, for example, was readily explained by the consideration that at the lower temperatures there were too few excited atoms to give appreciable absorption, whilst at the higher temperatures there were too few neutral atoms left to give any absorption; the actual intensity must depend on the product of two factors, the excitation factor and the ionization factor, of which the first factor, the fraction excited, must increase from almost zero, whilst the second factor, the fraction un-ionized, must decrease to almost zero. Thus the product, being zero at the two limits of temperature, low and high, must have at least one maximum in between, and probably only one. I rapidly expounded this to Fowler, and we said we would work it out for our joint paper. That evening I did a hasty order of magnitude calculation of the effect and found that to agree with a temperature of 10,000° for the stars of type A0, where the Balmer lines have their maximum, a pressure of the order of 10^{-4} atmosphere was required. This was very exciting, because standard determinations of pressures in stellar atmospheres from line shifts and line widths had been supposed to indicate a pressure of the order of one atmosphere, or more, and I had begun on other grounds to disbelieve this. I walked round to Fowler's house in the Chesterton Road, and finding him out dropped a short note in his letter-box telling him of this result. The next two or three days I was busy

over other matters, and when I next saw Fowler he told me he had read my note and had worked out an exact and elegant formula for the pressure at which the lines of a subordinate series of a neutral atom should have their maximum. I then assembled the astrophysical data at the Solar Physics Observatory, and produced a draft of the paper we eventually read to the Society.

I think this little story is typical of much of Fowler's work done in collaboration. The project was often his, the original idea of the paper was someone else's, but he so quickly digested it, transformed it, brought his technique to bear on it and developed it, that he became a full partner in the investigation. And I must add that without Fowler's tremendous drive, many such investigations would never have been brought to the stage of publication.

He and I published a further paper on the maxima of absorption lines in stellar spectra in 1924, extending the work to the successive spectra of ionized silicon (which had been sorted out by A. Fowler) and of ionized carbon. The maxima of these fixed the temperature scale for the B- and some O-stars, following earlier work of H. H. Plaskett. Fowler published a third paper alone in 1925. In 1925 too he collaborated with E. A. Guggenheim in applying the ionization theory in detail to stellar interiors. In 1924 I was in constant discussion with him on the *mechanism* of ionization in large assemblies, as opposed to the mere determination of the *degree* of ionization. We had both been impressed by Klein and Rosseland's isolation of the phenomenon known as "collisions of the second kind", in which the reverse of excitation by collision occurred. In a paper in the *Philosophical Magazine* I applied this idea to *photo-electric ionization*, and this was immediately followed by a paper by Fowler on the application of the same idea to *ionization by collision*. Briefly, if in a steady state some ionizations occur as a result of collisions, then there must be as many *three-body* encounters which result in the *re-attachment* of an electron to an ion, to balance them. We then recognized the complete generality of the "principle of detailed balancing"; the phrase was, I think, due to Fowler, though the importance of the principle was being simultaneously recognized elsewhere.

For an essay collecting together his work in statistical mechanics, Fowler was awarded the Adams Prize of the University of Cambridge in 1923–24. The material of this essay was later published by Fowler as a splendid volume, *Statistical Mechanics* (Cambridge, 1929), which reached a second (revised) edition, though shorn of its astrophysical applications, in 1936. This is a highly technical work, not easy to read, but a mine of information on all the thermo-dynamic properties of the various phases of matter and its environment of radiation—gases (perfect and imperfect), solutions, crystals, conductors, surface films and liquids. Its professional competence is amazing, and it is almost fatiguingly exhaustive. It and its successor volume, *Statistical Thermodynamics* (1939), with E. A. Guggenheim, should long remain standard treatises.

In 1926 Fowler published the most original paper of his lifetime, a paper read before the Society entitled "On Dense Matter", wherein he showed that the material in white dwarf stars must consist of a gas in what is called the *degenerate state*, *i.e.* a gas obeying the quantum statistics discovered independently by P. A. M. Dirac and E. Fermi. It had been recognized by astronomers (chiefly by A. S. Eddington) that a star like the companion of Sirius, with its typical stellar mass, high effective temperature and low absolute luminosity, must have a very small surface area, hence a small radius, and therefore a high density—incredibly high, by terrestrial standards, being of the order of one ton per cubic inch. Either a fundamental explanation had to be found, or there was something seriously amiss with the bases of astrophysical measurement. Fowler found the explanation: the atoms, ionized to almost bare nuclei, were pressed close together, and the free electrons formed a degenerate gas—as Fowler put it, "like a gigantic molecule in its lowest quantum state". About the same time L. H. Thomas recognized that the electrons in an ordinary atom of high atomic number could be described as a degenerate gas, and obtained an equation for its equilibrium of Emden's type.

Fowler did not go into elaborate calculations of the equilibrium of white dwarfs in this paper, though he later shared in the discussion of the polytropes "$n=\frac{3}{2}$" which were subsequently shown to describe them, in the paper on Emden's equation already described. Justly famous as this paper on dense matter afterwards became, it was always a slight source of chagrin to Fowler in that he did not also see at the same time a field for the application of Fermi-Dirac statistics to the assembly of free electrons in the interior of a *conductor*. It was left to Sommerfeld to revive the theory of electronic conduction by showing that the electrons in a solid metal conductor were not attached to particular atoms, but constituted a gas at an apparent very low temperature. A gas becomes degenerate when ρ/T^3 is large, and this may occur in a white dwarf star (where ρ is very high compared with T) or in a conductor where T (apparent) is very small compared with ρ; and Fowler once told me "he could have kicked himself" for not seeing this before Sommerfeld, when he had the idea under his thumb.

Differential equations, differential geometry, ballistics and aerodynamics, statistical mechanics, stellar atmospheres, stellar interiors, degenerate gases—these by no means exhaust the range of Fowler's interests even before he became professor. He had papers in the *Philosophical Magazine* in 1925–26 on the summation rules for the intensities of spectral lines and in band spectra; he wrote papers on the statistical theory of strong electrolytes, and became such an acknowledged expert on questions of physical chemistry that he eventually became a member of the editorial board of the newly formed *Journal of Chemical Physics*; he studied the thermionic and photo-electric emission of electrons from metals—hot, cold, clean and coated; he worked at ferro-magnetism and magneto-striction. But he did not confine his attention to his own researches. He was of immense assistance to the Cambridge schools of experimental and theoretical physics, and took up quarters at the Cavendish Laboratory. It was therefore inevitable that when the university wished to make an election to the newly instituted Plummer Chair of Theoretical Physics, it should turn to Fowler; and he was duly elected Professor in 1932 January.

His stream of papers continued unchecked. His own even closer association with Rutherford—he had examined α-particle problems in his earlier researches—led to his interesting himself in the absorption of γ-rays in elements of high atomic number; he wrote papers on various aspects of adsorption; he considered semi-conductors; he examined questions of surface tension; he delivered the Bakerian Lecture of 1935 on the specific heats of crystals; he expounded the theory of the separation of the isotopes of hydrogen by electrolysis. An excellent example of his well-informed style is afforded by his Liversidge Lecture of 1934 on the heavy isotope of hydrogen, wherein, on a subject not specifically his own, he assembled all the significant facts and figures relating to this new discovery—acting under superior orders, as he said. One may guess shrewdly that "supreme headquarters" consisted principally of Rutherford, who knew how to give Fowler rope for his activities. The lecture was published in the *Proceedings of the Cambridge Philosophical Society*.

He had been elected a Fellow of the Royal Society in 1925. He became a Fellow of Winchester in 1933. In 1936 he was awarded one of the Royal Medals. In 1938 he was appointed to the Directorship of the National Physical Laboratory, in succession to Sir Lawrence Bragg, who had succeeded Rutherford in the Cavendish Chair at Cambridge. No more competent person could have been chosen, and it was a tribute to Fowler's practical ability which he had handsomely earned; but that cannot lessen one's astonishment at such a complete transformation of the original pure mathematician into the physicist, engineer and administrator that the head of the National Physical Laboratory must be. It must be remembered that, apart from his early war experience of 1916–19, he had never performed a physical experiment in his life.

However, fate decided that he should not take up the appointment. In the summer of 1938 he received the first attack of the illness to which he eventually succumbed, and on

medical advice he resigned the Directorship before the Plummer Chair had been declared vacant. Consequently he retained the Plummer Chair.

In 1939 came the war. Fowler at once picked up the threads of his association with the Ordnance Board, and at considerable personal inconvenience often came up from Cambridge to attend its meetings at the place to which it was evacuated. In spite of the growing threat to his health, he was able as ever to master the complicated agenda of the Board meetings at a glance, was a tower of strength when difficult questions were referred to him, and could make members of the Board who had held high administrative positions in government research departments tremble at his words. Soon greater opportunities were given him. He was chosen to establish scientific liaison between research on war problems in service departments in this country and similar research in corresponding departments in Canada. One heard of his being here, there and everywhere. He was already familiar with Canada and the United States through numerous visits in peace time, having attended the Toronto meeting of the British Association in 1924 and on that occasion crossed to the Pacific, and having occupied lecturing posts at Princeton and Madison, Wis. Of the success, the very notable success, of his mission to Canada there could be no doubt; cabinet ministers referred to him in their speeches. He extended his mission to Washington, and, that completed, returned to England. For these services he was created a knight in 1942.

This self-sacrificing exertion, it is probable, shortened his life. But his activities did not slacken. Back in England he soon became a full-time member of a research section at the Admiralty. The last piece of collaboration I undertook with him, at his request, was an investigation of the relative destructive power of armour-piercing and high-explosive projectiles, when directed against a modern battleship. He was being consulted by the Ordnance Board on questions of shell-ballistics up to within a few weeks of his death. But the full inner story of his last months at the Admiralty is not known to the writer, and in any case would have to remain secret.

It is difficult to estimate the loss to British science caused by the premature death of one so accomplished and experienced as R. H. Fowler. Chairmanships of important committees had come to him; he had been editor (with P. Kapitza) of the Oxford series of monographs on physics; but the presidencies of important scientific societies, which would naturally have fallen to him, were still to come. His constructive, original work was perhaps completed. But the ripe comments on contemporary movements in science, the summaries of work by other men and in other lands, the wise direction of post-war scientific activities, his part in the revival of international scientific relationships, all of which he would have contributed from the unequalled width of his experience, we must sadly go without. A position of great and growing influence was already his; what it would have become we can only conjecture. We know only that we grieve for a prince amongst men.

He was elected a Fellow of the Society on 1922 November 10. E. A. MILNE.

[By courtesy of the London Mathematical Society, from whose *Journal* the above, itself an abridgment of that written for the Royal Society, is largely reprinted.]

PHILIP FOX, son of Simeon M. and Esther (Butler) Fox, was born in Manhattan, Kansas, on 1878 March 7, and died from cerebral thrombosis in Cambridge, Massachusetts, on 1944 July 21.

After receiving his B.S. degree from Kansas State College he enlisted for the Spanish-American War, and was promoted to a second lieutenancy on the field of battle for heroism in action against the Moros in the Philippines. He continued his military interest and connections, rose to the rank of Lieut.-Colonel and assistant chief-of-staff in World War I, and to a colonelcy in the present war.

Fox became Carnegie Assistant at Yerkes Observatory in 1903 and remained as

Instructor in Astrophysics until 1909, with one year of study at Potsdam during this period. He was Professor of Astronomy and Director of Dearborn Observatory, Northwestern University, until 1929, Organizer and Director of the Adler Planetarium and Astronomical Museum in Chicago until 1937, and Director of the Chicago Museum of Science and Industry until 1942, when he returned to the army.

Like many others, Fox was strongly influenced in his earlier professional years by such men as his cousin, Ernest Fox Nichols, the physicist, George Ellery Hale, Sherburne Wesley Burnham and Frank Schlesinger.

The inspiration of Hale led him into solar research, that of Burnham into micrometer work with double stars, and the example of Schlesinger into photographic determinations of stellar parallaxes, during his years at Yerkes.

All three of these interests were developed at Dearborn as massive programmes of research. The *Rotation of the Sun*, from measurements of the positions of calcium flocculi upon plates, which he took with the Rumford spectroheliograph attached to the 40-inch refractor, was completed and published from Yerkes in 1921.

At Dearborn he at once began the observation of double stars. The results for some 4200 double and multiple stars, including 102 discovered by himself, were published in Volume I (1915) and Volume II (1925) of the *Annals of the Dearborn Observatory*, which he started. A large number of additional observations made since 1925 remain to be published.

In 1912 he initiated a programme of observations for stellar parallaxes, which was completed by the publication (1935) of Volume III of the *Annals*, containing the results for 197 stars.

Like the great Burnham and Barnard whom he admired so much, Fox loved to observe regardless of physical discomfort, so long as the stars were out and the "seeing" useable. He was a keen, careful and critical observer, persistent and tireless in the prosecution of his programmes.

Few scientists have had so many outlets for artistic activity. He played the 'cello and pipe organ. He wrote songs in English and French, set them to music and sang them; painted, made pen-and-ink sketches and made a number of excellent etchings.

In all of his military, civil and scientific associations Fox's brilliant mind, marked spirit of generosity and keen sense of fairness and justice were qualities which notably endeared him to all who had the privilege of knowing him and working with him.

He is survived by his wife Ethel (Snow) Fox, whom he married in 1905, and by their four children, three sons and one daughter.

He was elected a Fellow of the Society on 1911 December 8.

O. J. LEE.

MURRAY GEDDES died in Glasgow on 1944 July 23, at the age of thirty-five, after a sudden and unexpected illness. He was the second son of Mrs. E. Geddes, formerly of New Plymouth and now of Taranaki, and the late Mr. J. Geddes. He was educated at New Plymouth Boys High School, the Dunedin Teachers Training College, and Otago University, where he took his M.A. degree in 1937.

Taking up the teaching profession as a probationer at the Westown School, New Plymouth, he soon became interested in astronomical subjects, and joined the New Plymouth Astronomical Society. Here he laid the foundations for his future career, and soon became prominent as an assiduous observer of meteors, sunspots and variable stars. Later, when his teaching work took him to Southland, he became interested in auroræ, and in 1932 was appointed Director of the Auroral and Zodiacal Light Section of the New Zealand Astronomical Society. In this capacity, and later as Director of the Carter Observatory, he began work which was bearing considerable fruit when he left the Dominion, and of which more could have been expected on his return. In collaboration with Professor Störmer of Norway, he made photographic determinations

of auroral heights, studied auroral forms, phases, frequency and statistics, and became actively interested in correlations between solar activity, auroral displays, magnetic disturbances and Earth currents. His work showed that auroral displays in the southern hemisphere are much more frequent than was formerly believed, and are sometimes even more frequent than the Aurora Borealis; secondly, that maximum auroral activity in the Aurora Australis lags a few years behind a solar maximum; thirdly, in conjunction with Professor White of Canterbury, N.Z., by studying the records of Antarctic Expeditions the auroral zone around the South Pole was plotted and it was shown that the South Island of New Zealand was the most favourable land mass from which to study the Aurora Australis, apart from going to Antarctica itself. He also organised a large team of voluntary observers throughout the length and breadth of New Zealand for this work, and some seven hundred names were on the registers of the Carter Observatory.

He joined the New Zealand Astronomical Society in 1931, becoming President in 1940–41, Vice-President in 1942–43, and was a member of the Council at the time of his death. He was a member of the British Astronomical Association, the Astronomical Society of France, and the American Meteor Society. With the formation of the Royal Society of New Zealand, be became Vice-President of the Southern Branch in 1938–39.

The discovery in 1932, while he was at Otakura, of the famous comet that now bears his name, brought him before the whole astronomical world. For this he obtained the Comet Medal of the Astronomical Society of the Pacific (U.S.A.) and later, in 1933, the Donovan Prize and Medal (Australia).

For the principal purpose of making observations of the Zodiacal Light and Gegenschein, he accompanied the eclipse expeditions to Pukekohe, Auckland, in 1936, and to Canton Island in the Central Pacific in 1937. He did first-class work on the day of the eclipse on each occasion. Concerning the Zodiacal Light, he held the opinion that it was an optical effect in the upper atmosphere, and he had many ideas and much data which unfortunately have not yet been published.

On 1939 March 7 he was appointed Director of the newly established Carter Observatory. The new observatory building was completed by December 1941, but just before the official opening he joined the Royal New Zealand Naval Volunteer Reserve, with the rank of Sub-Lieutenant, for specialist duties and left New Zealand in February 1942. During his time at the Carter Observatory he inaugurated the systematic measurement of double stars, and during the 1939 opposition of Mars made some notable observations which were published in *Popular Astronomy*. He also actively assisted in a proposed Astronomical History of New Zealand and was fast becoming an authority on Polynesian star lore and navigation.

While his home was among the stars he also had a place among men, and the diversity of his interests is shown by the fact that he was a member of the Forest and Bird Society, the Wellington Photographic Club, and the Tararua Tramping Club. In each of these organizations he was by no means a passive member but entered into their activities with enthusiasm. He was an expert mountaineer and deer stalker.

During his naval career he saw a good deal of action, being present during the first air raid on Colombo, the landings on Madagascar, and on convoy duties in aircraft carriers in the Mediterranean. He flew to the United States in connection with his work, and it was not long after this mission that his death occurred. His technical knowledge of radar and fighter direction, and his research ability, were so great that he was transferred to the Admiralty Signals Establishment with the rank of Lieutenant-Commander. He was held in the highest esteem, both personal and professional, by his colleagues and superior officers, all of whom lamented his untimely loss. There can be no doubt that he served the cause for which we are fighting with ability and distinction.

New Zealand has suffered a great loss in his death, and there will be many who feel the loss of a kindly nature and a good friend.

He was elected a Fellow of the Society on 1935 January 11. I. L. THOMSEN.

ALFRED MARSHALL GRAEME-THOM (b. 1886, d. 1943), a twin, came of a Scottish Highland crofter family with a long-standing military tradition. At the early age of fourteen years he volunteered for military service, enlisted in the Gordon Highlanders, took part in the Boer War and in the same year received the D.C.M., being probably the youngest holder of that decoration. Continuing on active service he distinguished himself in the field and in the air, playing a prominent part in the early days of the R.F.C., persisting in hazardous exploits in spite of serious wounds (and well-intentioned dissuasion), attaining at length the rank of Major and receiving, over the period of his service, numerous further military honours and decorations, including those of some of the highest European orders, namely, the Order of the Legion of Honour, the Order of St. Anne of Russia, and the Order of Leopold of Belgium. His military career was terminated in 1918 by the effects of a severe head wound which, on his return to civil life, caused him eventually to seek refuge in a solitary existence on his own estate, an extensive virgin terrain in a remote part of the East Gippsland "bush," Australia. Here he first devoted himself to the cultivation and curing of tobacco and to research in this subject, in which he was known to have a specialized knowledge. Here also he could indulge his love of nature and profit by his skill as an accomplished archer, using only bows of his own fashioning, while developing an interest in astronomy, especially as an observer of meteors.

For reasons of health Thom was eventually compelled to abandon the production of tobacco and thereupon decided to give full rein to his passion for astronomical observation. He then resolved to construct and equip a second and larger observatory. Having already considerable mechanical skill, he proceeded to perfect his knowledge of optics and cultivated this subject assiduously from both its theoretical and practical aspects. He experimented with success in the production of specula for mirrors and gratings and had already achieved a considerable measure of optical and instrument-making proficiency when, impelled by his craftsman's interest and thirst for optical knowledge, he was able, by virtue of sustained self-denial—in which he was aided by his wife, a lady of Gippsland descent—to arrange a world tour for the purpose of visiting the most important centres of optical instruction and production. This brought him in 1938 to Europe, where he worked for a time at various optical firms, including those of Messrs. Chance Bros. of Birmingham and Messrs. Hilger of London, after having travelled widely in Britain, France, Germany, Italy and Russia. The first contemplated completion of his plan by a visit to the great optical centres of the U.S.A. had to be abandoned owing to the exigencies of the present war. Thom and his wife lost their lives by enemy action on making the return journey to Australia, where Thom was to have taken up an appointment in which his newly developed optical ability would have been of value to the Empire's cause.

The discriminative knowledge gained from his intensive study and application to the craft and science of optics procured him many minor triumphs in this field, made him a keen judge of values therein and enabled him to contribute materially to the war effort in this country. Thom's capabilities in optics were not yet plumbed and his work in astronomy was not yet accomplished when in 1943, in his fifty-seventh year, he met his tragic death at sea, but his example as an amateur, in the true and literal sense of the word, is in the best traditions of astronomy and optics.

He was elected a Fellow of the Society on 1942 July 10.

J. W. PERRY.

HENRY ERNEST GREEN, Second Assistant in the Cambridge Observatory, died suddenly at Cambridge on 1944 September 18, at the age of fifty-five. Born at Greenwich on 1889 August 2, he was the third and youngest son of Charles and Esther Green. He was admitted to the Royal Hospital School, Greenwich (Upper Nautical School), as

a Sir William Boreman Foundation Scholar and later he was awarded a William Boreman Exhibition. Green started his astronomical career in the Royal Observatory, Greenwich, in 1905 as a computer in the Time and Chronometer Department, and subsequently his duties included observing with the Transit Circle and the Astrographic Telescope. He was a member of the Observatory hockey eleven until 1907, contemporaneously with the late Sir Arthur Eddington, a serious illness (rheumatic fever) in that year putting an end to his athletic activities. His health thereafter was never robust, and in 1912 he was unable to pass the medical examination for appointment on the permanent establishment of the Royal Observatory. Between 1912 and 1914 he was an assistant in the well-known firm of J. H. Dallmeyer Ltd., being mainly occupied with the computing and testing of lenses. Green had always a high sense of duty and, on the outbreak of the first world war, he volunteered for military service, being rejected, however, on medical grounds. From 1914 September he was employed on the computation of tides in the Tidal Branch of the Hydrographic Department at the Admiralty until 1918 May, when he resigned in order to accept Sir Arthur Eddington's invitation to join the Observatory staff at Cambridge as Second Assistant, a post he held until his death. He joined Fitzwilliam House in 1921, taking his B.A. degree in 1924 and his M.A. degree in 1927.

Green's principal work during his first year or two at Cambridge was the completion of the reductions, then considerably in arrears, of the Transit Circle observations (made between 1900 and 1918) for the Zodiacal Catalogue of Stars; he was chiefly responsible for the preparation of the catalogue which was published in 1928, after some delay, as Volume XXIV, Part II, of the *Cambridge Observations*. The midsummer of 1919 saw the beginning of a happy association of eighteen years between Green and the writer, first in an extensive programme of photographic proper motions and second in the photo-electric photometry of variable stars. Green was a first-rate observer and computer and his optical experience with Dallmeyer's proved invaluable in the practical details of observatory work. Much of the success of the photo-electric programme was due to him for he quickly mastered the tricky equipment and was responsible for many practical improvements.

Green contributed papers to *Monthly Notices* on the ultra-violet spectrum of Nova Herculis (1934) and on photo-electric observations of 12 Lacertæ, and collaborated with the writer in papers on the analysis of proper motions, the solar motion and galactic rotation, with E. G. Williams on the colour temperature of Nova Herculis (1934), and with H. A. Brück on the radial velocity curve of δ Cephei.

Green was quiet and modest, conscientious in everything he did, keenly interested in observatory affairs, a most agreeable colleague and kindly in all human relationships. He married in 1929 May Louise Pretoria Dow by whom he is survived.

He was elected a Fellow on 1935 March 8.

W. M. SMART.

SAMUEL MORRIS GREEN, serving in the R.A.M.C., was killed in action with the British Liberation Army, 1944 June 6, after less than six months in the service. Born 1921 August 10, he was educated at Bromsgrove and Liverpool University, where he graduated M.B. with high honours in 1942, taking up a hospital appointment at Fazakerley. His other interests were photography and astronomy. He used a 12-inch reflector of his own construction, which he devoted mainly to systematic study of areas of the Moon. His detailed study of the region Sven Hedin and other contributions, which it is hoped will be published in the *Memoirs* of the British Astronomical Association, show that we have lost in him one of the most promising and accurate selenographers of our time. He was an active member of the British Astronomical Association and the Manchester Astronomical Society; he was also a member of the Société Astronomique de France. He had in full measure the modesty which often goes with

high promise; but his friends and correspondents will not forget his keen eager mind and happy disposition.

He was elected a Fellow of the Society on 1939 February 10.

T. L. MACDONALD.

JACOB KARL ERNST HALM was born on 1866 November 30 in Bingen, Germany. After the usual education in a Gymnasium, he spent four years at the Universities of Giessen, Berlin and Kiel. His early interest was in mathematics, and he carried out investigations on the mathematical theory of tides in lakes and on the structure of the series in line and band spectra. He graduated Doctor of Philosophy at Kiel. Halm was an accomplished violinist, with a great interest in chamber music; through this interest he was brought into close friendship with the Director of Kiel Observatory, Dr. A. Krüger, and for a time he was connected with the publishing office of the *Astronomische Nachrichten*. On the recommendation of Dr. Krüger he was appointed in 1889 Assistant at the Strasburg Observatory. He remained there for six years, being engaged chiefly on observations with the meridian circle and the heliometer and on the reduction of these observations. Over one-third of the observations for the Strasburg A.G. Zone ($-2°$ to $-6°$) were made by Halm.

In 1895, Halm was invited by Professor Copeland, Astronomer Royal for Scotland, to accept appointment as a First-Class Assistant at the newly erected Royal Observatory in Edinburgh. He accepted this invitation, and assisted in the mounting and adjustment of the instruments. For several years he was occupied with micrometric observations with the 15-inch refractor and with meridian observations of the zodiacal stars. In 1901 he commenced an extensive investigation by spectroscopic methods of the rotation of the Sun in various heliographic latitudes; these observations were continued until the year 1906 and covered the period from sunspot minimum until past sunspot maximum. They thus filled the gap between Duner's observations at Upsala, which ended in 1901, and Adams's observations at Mount Wilson, which commenced in 1906. The Edinburgh observations were in close systematic agreement with the corresponding almost contemporaneous observations at Upsala and Mount Wilson, but in each latitude the annual mean rate of rotation showed fairly progressive changes, which were greater in higher latitudes. Halm found that the changes in the annual means were too large and systematic to be attributable to errors of an instrumental or personal character, and concluded that the same law of rotation of the reversing layer can be expected only under similar conditions of solar activity. For this work he was awarded the Brisbane Gold Medal by the Royal Society of Edinburgh.

During much of this time Professor Copeland was unable to take an active part in the administrative and scientific work of the observatory, because of an illness which culminated with his death in 1905. Halm during these years not only supervised the general administration but also undertook Copeland's professional duties in the University. He carried out, in addition, a new reduction of the meridian observations made at Edinburgh by Henderson and his assistant during the years 1835–45.

Consequent on Gill's retirement from the Cape Observatory in 1907 and the promotion of Hough from Chief Assistant to H.M. Astronomer, Halm was selected, on Gill's recommendation, for appointment as Chief Assistant at the Cape Observatory, primarily because of his experience in spectroscopic work. He remained in that post until his retirement, under age regulations, in 1926. Halm entered fully into the varied work of the observatory; he shared in the observations with the Victoria telescope and the heliometer, and carried out a variety of investigation in many fields of astronomy.

In collaboration with Hough, the first investigation of the phenomenon of star-streaming based on radial velocities (determined at the Cape and Lick Observatories) was made, and evidence of a third drift, with which the B-type stars are closely associated, was found. In a series of investigations on the distribution of the stars and their

luminosities, Halm concluded that absorbent matter, confined to a comparatively narrow equatorial galactic belt, was partly responsible for the apparent falling off in star density outwards from the Sun, and was able to assign an upper limit for this absorption of 2·1 magnitudes per kiloparsec. He showed that there was approximate equipartition of energy amongst the stars, and was the first astronomer to suggest the existence of a mass-luminosity relationship. He also obtained evidence that there exist certain preferential stellar masses.

Halm carried out many investigations in photographic photometry, with the aim of establishing a system of photographic magnitudes which could be used as a basis for standardising the magnitudes of the Cape Astrographic Zones, $-40°$ to $-52°$. These investigations were based on Kron's researches into the laws of photographic action. A south polar sequence of magnitudes was established, which agreed in scale and zero-point with the north polar sequence, within the accuracy which the comparisons, through the intermediary of Harvard data, permitted; the magnitudes of the CPD were standardised and it was found that the scale value of the CPD showed considerable fluctuations, which in part depended upon the relation of the stars to the Milky Way. The magnitudes of the CAZ were standardised.

Halm did much to encourage interest in astronomy in South Africa. He took an active part in the Astronomical Society of South Africa and was always ready to give advice and assistance to amateur observers. The Society published a booklet by him entitled *A Universal Sundial*; by following his instructions, many amateurs succeeded in constructing for themselves a sundial which would give accurate local apparent solar time in any part of the world. Before the days of broadcasting, these sundials proved very useful in checking clocks in isolated communities in South Africa.

After his retirement from the Cape Observatory Halm settled in Stellenbosch, and for several years gave lectures on Astronomy to advanced students at the Stellenbosch University.

Throughout his life Halm was an enthusiastic musician, with a special love of chamber music. He played the viola at the concerts of the Chamber Music Union in Cape Town, but he was equally at home playing on his much-treasured Amati violin. He was a man of great personal charm. During the war of 1914–18 conditions at the Cape were difficult for him, though he was a naturalised British subject and his entire sympathies were with the British cause. He married, in 1894, Hanna Bader, of Basle, who with one son and two daughters survive him.

Halm was elected a Fellow of the Society on 1906 May 11 and resigned in 1940. He died on 1944 July 17.

H. SPENCER JONES.

SAMUEL VERPLANCK HOFFMAN was born in Brooklyn, N.Y., on 1866 May 12. After graduating in mechanical engineering in 1886, he worked for a year at the College of Physicians and Surgeons in New York and then, in 1889, he entered the graduate department of Johns Hopkins University, where he was appointed a student assistant in Astronomy and later a Fellow in Astronomy.

His main interests, however, turned in other directions. His business career was mainly devoted to the management of his father's extensive property in New York City, and he found time to belong to many clubs, hereditary and patriotic societies. He was a member of the New York Historical Society for over forty years, and served as president from 1903 to 1913. This society's gold medal, of which but three have been struck, was awarded to him in 1933 for "Distinguished Service".

His chief hobby was collecting astrolabes, and one of his most prized possessions was the one used by Samuel de Champlain on his early American explorations.

He died in New York City on 1942 February 23, leaving a widow, one son and one daughter.

He was elected a Fellow of the Society on 1895 March 8.

THOMAS HERBERT LE SBIREL HONY was born on 1866 May 25 at Liskeard in Cornwall, and from his earliest youth was interested in Astronomy as an amateur observer. He was educated at Wadham Grammar School, Liskeard. He was a banker by profession and for thirty years was manager of Lloyds Bank at Fowey, where he died on 1944 November 27. Hony was well known throughout the West Country for his articles on astronomical subjects in the local newspapers; his articles were always accurate and maintained a high standard of interest. Many Fellows will remember the characteristic calligraphy of the letters which he wrote seeking information and data for his articles.

He was elected a Fellow of the Society on 1922 May 12.

DONALD WILLIAM HORNER, whose sudden death occurred on 1944 February 28, had been for many years an enthusiastic meteorologist. He specialised in long-distance weather forecasting for the press, but unlike many of his rivals Horner did not keep his methods secret. In publishing them for all to see and criticise he showed his true scientific spirit.

An able and conscientious observer, he contributed many articles to meteorological publications and to the general press. He was also author or part author of many elementary instructional books on meteorology and astronomy.

He was elected a Fellow of the Society on 1920 April 9.

STANLEY MAXWELL was born at Cambridge on 1875 September 13. He was educated at Manor House School, Clapham Common, of which his father, Dr. F. C. Maxwell, was Founder and Headmaster, and at St. John's College, Cambridge. In 1898, shortly after taking the degrees of B.A. and LL.B., he took over the Headmastership of his father's school, over which he presided with great success for the next forty years. In 1938 he decided, for various reasons, to close the school altogether, and went to live at Surbiton, where he died on 1944 September 20.

Maxwell's interest in education was far from being restricted to the conduct of his own school, and his name was widely known and respected in scholastic circles. Throughout his career he was a great champion of the cause of the independent school and was from 1909 to 1939 Chairman of the Private Schools Association, his colleagues on the Council speaking warmly in appreciation of his services during this period. He also served on the Departmental Committee on Private Schools, set up by the Government in 1930. His activities in the sphere of education did not cease with his retirement from actual teaching, for in 1938 he became Secretary of the College of Preceptors, a position which he held up to the date of his death.

Though his preoccupation with matters scholastic made great demands upon his time, Maxwell devoted much of his scanty leisure to Astronomy. His professional work made it impossible for him to attempt any serious original contributions to the subject, but his continued interest was shown by his regular attendance at the meetings of the Society and of the British Astronomical Association, of which he was a prominent member, having sat for many years on the Council and having served as Secretary from 1917 to 1923. His many friends in both Societies will remember him as a man of sound judgment and unfailing courtesy.

In 1900 Maxwell married Edith Marion Allen, daughter of the Rev. Richard Allen. She survives him, with three sons.

He was elected a Fellow of the Society on 1910 February 11.

W. H. STEAVENSON.

HUGH FRANK NEWALL was born on 1857 June 21 at Gateshead-on-Tyne. His father was Robert Stirling Newall, F.R.S., inventor and manufacturer of wire ropes, who constructed most of the first submarine cables and personally took part in the laying of them. His mother was a daughter of Hugh Lee Pattinson, F.R.S., who invented a process for desilverising lead. Mr. Pattinson had a $7\frac{1}{4}$-inch equatorial by Cooke of York—a large telescope in the days when a 15-inch was the largest refractor in existence. This may well have inspired Mr. Newall, who had wide scientific interests and had already made a series of drawings of the Sun, to seek for an opportunity to construct and mount a very large refractor. At the Exhibition of 1862 he saw and acquired two rough disks of crown and flint glass exhibited by Messrs. Chance of Birmingham; these were sent to Cooke's for figuring and were shown at the British Association meeting at Newcastle in 1865. It was not till 1871, however, that the dome and mounting were finished, and the 25-inch equatorial telescope of 29-foot focal length was erected in an observatory set up in the garden of Newall's home at Ferndene.

When Frank Newall left for Rugby School in 1872 the telescope which was to mean so much to him throughout his later life had just come into full being. But neither at school nor in his years (1876–1880) at Cambridge, where he graduated in Mathematics, did he show any leaning towards becoming an astronomer. His marriage in 1881 with Margaret Arnold, daughter of his old housemaster, was probably not unconnected with his going to Wellington College as an assistant master. Before he left Wellington in 1883 he had published his first paper on "Internal Reflexions in the Eye" (*Proc. R.S.*, Jan. 1883) in which his power of observation and keen interest in natural phenomena were both clearly evidenced. He and Mrs. Newall travelled abroad, staying for some time in Perugia, and meanwhile Newall published two more papers showing his interest in simple phenomena, observed under experimental control. The first was on "Colliding Water-jets" and the second on the "Formation of Vortex Rings by Drops falling into Liquids". This paper was written jointly with J. J. Thomson, Cavendish Professor of Experimental Physics at Cambridge University, who invited Newall to join him as Assistant and Demonstrator of Experimental Physics in succession to Richard Threlfall: his colleagues were Glazebrook, Napier Shaw, and Randell. Newall returned to Cambridge in 1881 October, to reside there for the rest of his life. The subjects of his next three papers still showed no sign of his future career; they were "Electricity Leaking through Badly Conducting Liquids" (with J. J. Thomson), "Peculiarities of Iron and Steel at Bright Red Heat", and "Recalescence of Steel".

Then came a series of events which entirely altered his life. His father had always intended that his great telescope should be transported to a southern climate, but various offers which he had made from time to time for its use under more favourable conditions than obtained at Gateshead had failed for one reason or another. Amongst these offers was one in 1876 for use at a proposed Physical Observatory, "for application to the development of Physical Astronomy", and another in 1879, when Gill was going out to succeed Stone as His Majesty's Astronomer at the Cape, for a seven years loan to the Cape Observatory. This latter offer was rejected on the ground that the expense involved, £3000, was unduly high for the use of a borrowed telescope. Finally on 1889 March 4, a month before his death, Mr. R. S. Newall wrote to the Vice-Chancellor of the University of Cambridge offering the telescope to the University. He said that the telescope had done "no systematic work in its present position owing to unfavourable atmospheric conditions and other reasons"; he further expressed a wish to place it where it would work under capable direction and hoped that the possession of an instrument especially adapted to the study of Stellar Physics might give impetus to the development of the subject. Subsequent history shows to what an extent these hopes were realised.

The University appointed a Syndicate to consider the offer, the members being Adams, Routh, Glaisher, Liveing, Darwin and Thomson. A favourable report on the telescope's qualities from Christie, Common and Graham (first assistant observer at

the University Observatory) led the Syndicate to recommend the University to accept the offer and to call the telescope "The Newall Telescope". But difficulties of a financial nature arose in the matter of the expenses involved in the move and in the staffing of the observatory. Newall, anxious to see his father's telescope put to full use, offered the syndicate £300 towards the initial expenses and in addition his services as observer for five years without stipend, if he could find a site for a house near to the observatory, or, if he could get no house nearby, a sum of £200 a year towards the annual expenses. The Syndicate recommended the University to accept this offer and to appoint Newall as observer "conditionally on his providing himself with a residence within" 500 yards of the observatory. The University accepted the recommendation and thus came into existence a house, "Madingley Rise", well known to many astronomers from all over the world for the following fifty years. Here the Newalls extended gracious hospitality to a wide circle of friends, and one might meet astronomers from overseas—Backlund, Campbell, Gill, Hale, or Michelson to mention only a few—or British scientists—Dyson, Fowler, Huggins, Parsons, Turner —or musicians who kept alive the link between Mrs. Newall and Joachim. Madingley Rise became a centre of culture in Cambridge, acquiring in later years an old-world accent; symbolical of this and of Newall's conservative outlook on life was his carriage and pair driven by the faithful Arthur and surviving long after the incoming of the motor-car. On his death Newall bequeathed his house to Trinity College.

Newall resigned his demonstratorship in 1890 and was largely occupied for the next two years in superintending the move and re-erection of the telescope and dome. It is not without interest that the erection of the new telescope led to gas being laid on to the main University Observatory. Newall became a Fellow of the Society on 1891 June 12 and published his first paper in the *Monthly Notices* in 1892 May, a note on the "Comparison of the Magnitudes of Nova Aurigæ and neighbouring Stars" during 1892 March and April. His first report as Newall observer was made to the University in 1892 June and to the Society in the Council Report for 1893. Pending the arrival of new clockwork from Grubb's to improve the driving of the telescope Newall made observations on planets, Barnard's satellite of Jupiter and Swift's comet 1892 *a*. But he had not forgotten his father's wishes that the telescope should be devoted to physical astronomy, wishes entirely in accord with his training and outlook as an experimental physicist. His second paper in the *Monthly Notices* was on "A Diagram for use in adjusting a Diffraction Grating Spectroscope"; with the aid of two objective prisms lent by Norman Lockyer he began obtaining bright-star spectra, while he set to work on the task of designing a spectrograph for use with the telescope.

Much preliminary work had to be done which found expression in a "Note on Stellar Photographs secured with a Visual Telescope"; the effects of chromatic aberration, spherical aberration, varying aperture and of the use of different photographic plates were studied, and he became convinced of the paramount need for a correcting lens to meet the troubles due to chromatic aberration of the object-glass of the telescope. Ultimately he decided to use a single concavo-convex Cooke lens which brought the focus of the telescope to a point 18 inches inside the tube. This has a number of advantages which Newall was quick to seize. The attachment of the spectroscope to the telescope was strengthened, the whole spectroscope and the correcting lens slid in and out for focusing, the convergence of the cone of rays from the object-glass was reduced and a gain in convenience of handling the instrument was found in improved clearance from the observing platform. On the other hand, with the slit inside the telescope devices had to be designed for seeing the image of the star on the slit and for getting the comparison spectra on the plate. Huggins's plan of a reflecting slit plate of speculum metal was adopted, and much ingenuity was shown in the subsidiary optical train required to overcome the inaccessibility of the slit.

Newall did not take long to decide that objective-prisms were not suitable for use

with a telescope of so long a focus as 29 feet, and experiments on different prism arrangements led to a further decision against a direct vision type of spectrograph owing to the loss of light in the dense flint prism. Being anxious to make use of the still exceptionally large light-gathering power of the telescope for work on fainter stars, he adopted the plan of a single-prism slit spectrograph. The cost of this instrument was borne by a gift received from Miss Bruce's Grant in Aid of Astronomical Research. The offer came from E. C. Pickering of Harvard to Adams for the purchase of an instrument for the Cambridge Observatory. Ultimately the gift was made through Ball, who had meanwhile succeeded as Director of the University Observatory on the death of Adams. In recognition of the American source of the money required for the Bruce spectroscope, as Newall called it, the optical parts, save a telephoto lens made by Dallmeyer, came from Brashear's of Allegheny. The mechanical parts were made by the Cambridge Scientific Instrument Company. (The spectrograph was described in *Monthly Notices*, 56, 98, 1896, and the paper was repeated in the *Astrophysical Journal* as No. XVII in a series of articles on "The Modern Spectroscope".)

The chief activity of Newall during the years 1893–6 had been in connection with the design and testing of the new spectrograph. But he wrote in addition a paper on the spectrum of Argon (*Ap. J.*, 1, 372, 1898) and a further note on the formation of photographic star-disks; also he carried out such visual observations as micrometer measures of Phobos during the opposition of Mars of 1894 and occultations of stars during the total lunar eclipse of 1895 March 10. In 1895 too he made an observation at Riffelberg which was to colour his views of solar physics over many years. Observing the Sun through a spectroscope he saw isolated islands of the C line of hydrogen displaced towards the red. Violent local downrushes of hydrogen on the Sun were seen, some of which persisted for many hours. For long this remained an isolated observation, though of recent years it has been confirmed by the work of McMath, Lyot and others. An echo of Newall's own observation and consequent speculations is to be heard in a paper published by the Royal Society in 1897 on "Luminosity attending Compression of certain rarefied Gases". Here he suggests that gradual streaming-in of rarefied gases might give a pressure-glow which could account for the maintenance of luminosity and persistence of outline of the gaseous nebulæ. The speculation is to be judged in the light of our ignorance at the time of the nature of the nebulæ and of the sources of luminosity in gases. It gave evidence of a mind alert to apply new results to old problems.

Newall, who had commenced forty-three years continuous service on the Society's Council in 1893, was elected Secretary in 1897 *; in which year he offered to serve a further term of five years as Newall Observer without stipend. In announcing his generous offer the Observatory Syndicate expressed the view that the provision of a stipend for the Newall Observer was an urgent claim on the funds of the University. In 1896 and 1897 Newall commenced a study of stellar velocities in the line of sight only to run into serious difficulties through systematic trouble due to deflection of the collimator. The work was suspended while Newall was away in India observing a total solar eclipse and was renewed in 1899 July with higher dispersion obtained with the aid of a 4-prism spectrograph which had replaced the Bruce spectrograph. An early result was the discovery that *Capella* was a spectroscopic binary, a discovery made independently by Campbell at the Lick Observatory. Full details of Newall's observations were given in the *Monthly Notices* in 1900 March; they gave a period of 104 days and also estimates of the mass and absolute brightness of *Capella*.

Fresh calls upon Newall at this period came in connection with instrumental developments in the University Observatory; he served with Stokes and Ball on a committee on the New Photographic (Sheepshanks) Telescope, taking his share in the discussions on the design of the instrument and its building, and he also shared some of the diffi-

* He wrote the note on Stellar Spectroscopy for the Council's annual report every year, save one year of his Presidency, from 1898 to 1920.

culties that faced his nephew, Bryan Cookson, in the design of the Cookson Floating Zenith Telescope. Preparations for solar eclipse expeditions, the actual expeditions themselves and the preparations of subsequent reports all took their share of his time and energy. At this juncture we may turn aside from the narrative of his life to discuss his eclipse activities.

The first solar eclipse that Newall observed was at Pulgaon, India, on 1898 January 22. Mrs. Newall, as always, accompanied him on the expedition and shared in the observations. Captain E. H. Hills, R.E., was the other member of the party and Captain G. P. Lenox-Conyngham, R.E., was officer in charge of the eclipse camp. A 4-prism spectrograph with two slits mounted on a polar heliostat was used for an examination of the rotation of the corona, and a study of flash and coronal spectra on the two limbs. No trace of the coronal spectrum was found, but flash spectra were obtained. An objective-grating telescope was used for visual observation of the green coronal ring. No fine radial coronal structure was observed, but broad patches of light, coinciding roughly with marked broad extensions of the photographed corona and not with prominences. First attempts were made with Nicol prisms and attached Savart plates to study visually the polarization of the corona and the surrounding sky. Fundamentally these were the subjects of Newall's observations during most of his subsequent eclipse expeditions.

His second expedition was with Turner to Bouzareah, in the grounds of the Algiers Observatory for the eclipse of 1900 May 28. The 4-prism spectrograph was used with a polar heliostat for flash and coronal spectra at both contacts, this time with one slit instead of two. Twelve plates were used and changes in the flash spectrum noted from plate to plate. The absence of Fraunhofer lines in the coronal spectrum was noted as surprising, as strong bands were found over the corona photographed through a Nicol prism and Savart plate set for extinction of the sky bands. Mrs. Newall observed, using small Savart polariscopes, the polarization of the sky in points symmetrically disposed round the Sun.

The next eclipse observed by the Newalls was on 1901 May 17–18 at Sawah Lorento in Sumatra. This eclipse was marred by the presence of thick cirrus clouds which spoilt the high dispersion spectra of chromosphere and corona. Photographs taken through a double tube camera, with a Nicol prism and Savart plate in front of one lens, showed marked polarization of the corona. Good plates were secured with an objective-grating camera, while visual observations of the coronal ring again showed no fine structure.

Better weather awaited Newall at the eclipse of 1905 August 30 which he observed at Guelma, Algeria. Visual observations of the plane of polarization of the Earth's atmosphere were made early in the eclipse to help in setting the polarisers used in the photographic work for extinction of the sky bands. It was noted that the atmosphere diffused as much polarized light as the corona at 1·5 diameters from the limb. Photographs taken through a Nicol prism and Savart plate showed atmospheric polarization in step with coronal polarization in two quadrants, and out of step in the other two quadrants, confirming the visual observations that the sky polarization was horizontal and the coronal polarization radial. Polarization could be traced as close in as 1′ from the limb. No Fraunhofer lines were found in the polarized spectra secured with a single-prism spectrograph in front of which was placed a large double-image prism. It was noted from a comparison of direct photographs with polarized images taken through Nicol and Savart cameras that polarization varied through the corona, being weak in the arches and strong in the streamers. Abney standard squares were used on many of the coronal plates, as also in the 1901 eclipse.

Of the four eclipses observed between 1898 and 1905 only preliminary reports were ever published. Owing to pressure of other commitments Newall never found the opportunity to settle down to a final detailed study of his material. A recent study by

Brück (*M.N.*, **104**, 33, 1944) of the brightness distribution in a direct photograph of the corona secured at Guelma (in a paper read to the Society at the meeting at which Newall's death was announced), points to the existence of important eclipse material of Newall's still well worth studying.

With his intense eclipse activities in the years 1898–1901 it would not have been possible for much other work to be produced, but we may note a thorough study of the scale for a new Zeiss comparator for measuring spectra, a study of an unconfirmed variable radial velocity for α Persei, the fluctuations being ascribed by Newall to temperature changes, a set of spectrograms secured of Nova Persei 1901 and the addition of an annex on the north side of the dome to give opportunities for students to take part in the work of the observatory. In 1902 a gas engine and dynamo were installed in this annex for use in spectroscopic observations.

Newall continued to work on line-of-sight velocities in co-operation with Frost of Yerkes and directors of other observatories, but this work, as we shall see, got gradually crowded out by fresh developments in his activities. He had been elected a Fellow of the Royal Society in 1902, and on 1904 February 11 he was appointed to the Honorary Office of Assistant Director of the University Observatory. A full description of the 4-prism spectrograph used in the various eclipse expeditions and of the Newall telescope was given by Newall (*M.N.*, **65**, 636, 1908) following an important paper on the general design of spectrographs to be attached to equatorials of large aperture. This had special application to the effect of tremor disks and dealt with the diffraction method of estimating slit-width and the conditions for the economic use of light. In the struggle between the need for a wider slit for more light and the necessary larger train of prisms with more consequent loss of light, Newall sums up in favour of a narrow slit and shorter prism train. He also expresses a view in favour of a reflector with diffraction-grating spectrograph as suffering less from general atmospheric troubles than a refractor and prism spectrograph.

In 1905 a new chapter in the history of astrophysics at Cambridge opened up with the munificent bequest of £5000 from Frank McClean for the improvement of the instrumental equipment of the Newall Observatory. A special McClean Fund was founded, the observer in charge of the Newall Observatory to make, subject to the approval of the Observatory Syndicate, applications for grants for specific purposes. Newall began a special study of the suitability of atmospheric conditions for solar spectroscopic work. The Newall telescope was temporarily adjusted for solar observations, a grating being mounted instead of prisms, and a 4-inch finder being used with a projection screen to assist in the orientation of the telescope. Later the object-glass was dismounted for horizontal projection of a solar beam from a cœlostat and sunspot spectra were studied with a Cooke spectrograph formerly used by Piazzi Smyth and put at the disposal of the observatory by the Royal Society. A new observing hut was erected on the south side of the Newall dome for the cœlostat.

The growing development for solar work, the accumulation of observational material and the need to supplement the telescope by the laboratory led the Observatory Syndicate at this stage to propose the appointment of an assistant of University standing. Hitherto Newall had worked single-handed save for one laboratory assistant (A. W. Goatcher 1892–1901; H. J. Bellamy 1901–5; W. H. Manning after 1905; L. J. Stanley joined for solar work in 1906). Now an assistant in Astrophysics, whose University stipend was augmented by Newall, was appointed, the first holder of the post being Bryan Cookson.

The trials of conditions for solar spectroscopy were decisively favourable and from the McClean bequest the expense of a new installation was found. A cœlostat was set up in the hut south of the dome, a 12-inch lens of 60-foot focal length sent a beam horizontally across the dome to a Littrow grating spectrograph mounted in the north annex. Work was commenced on laboratory spectra under varying physical conditions and on bands in the solar spectrum, notably the cyanogen band at 3883 and the bands in

the red. Foreign students began to appear at the observatory, among others R. Rossi from Italy and Hubrecht from Holland. The latter worked on solar rotation, a subject in which Newall had long been interested. The Presidency of the Royal Astronomical Society 1907–9 and a Fellowship at Trinity College in 1909 bore witness to the growing appreciation of the work that Newall was doing for Astrophysics.

Next, on 1908 November 12, came an offer from the Royal Society, made on the suggestion of Sir William Huggins, that the telescopes and spectroscopes provided for his use under an endowment at the disposal of the Society should be presented as a gift towards the astrophysical equipment of the observatory. Huggins had found it necessary to discontinue active astronomical observations. This offer was accepted by the University, money was found (partly from anonymous sources) for the erection of a dome to house the telescopes with which Huggins had carried out his pioneer researches; in addition a Huggins observer's room, a computing room and library, and a small room for the head of the Astrophysical Department were constructed. The new building was called the Astrophysical Building and it had the Huggins dome placed at one end of it. Huggins did not live to see the transfer of his instruments completed, but he and later Lady Huggins made valuable additional gifts of instruments and photographs. Another valuable gift following on the Royal Society's came from Major E. H. Hills for the use of Newall and his successors; this included a 4-prism quartz spectrograph with 5-inch quartz objectives, a heliostat with 12-inch mirror by Common and other prisms, lenses and accessories.

At this stage the University felt the need for further recognition of Newall's status. A Chair in Astrophysics without stipend was established, and Newall was elected as Professor of Astrophysics on 1909 June 15. In that year he founded the Observatory Club for meetings of staff and students, and in 1910 a small book on *The Spectroscope and its Work* was published (S.P.C.K.).

From now on Newall retired gradually from active night work, but he continued to observe the Sun with the McClean equipment. Fresh responsibilities and administrative cares were coming his way, for on 1911 October 23 a letter was received by the Vice-Chancellor of the University from the President of the Board of Education conveying a recommendation made by a departmental committee that the Solar Physics Observatory, which had to be moved from South Kensington, should be transferred to Cambridge. The members of the committee who made the recommendation were Sir Thomas Heath, Sir Frank Dyson and Sir Arthur Schuster; Sir Richard Glazebrook dissented from their view. The committee stated that "having regard to the advantage to the progress of Solar Physics which may be expected to accrue from the establishment and support by the University of a real school combining the study of Solar Physics and Astrophysics the Cambridge scheme is calculated to give the better results". One condition laid down was that the Professor of Astrophysics should be the Director of the Solar Physics Observatory, the previous Director, Sir Norman Lockyer, having retired. An annual grant in aid was paid to the University and an initial grant for building. The Astrophysical Building was enlarged by the addition of a laboratory, workshop, dark room, staff rooms and a house for a resident attendant. Separate buildings were added for the 3-foot Common reflector and the spectroheliograph. The new buildings for the staff and the laboratory were ready when the Solar Physics Observatory was taken over by the University on 1913 April 1. One more gift has to be recorded—a gift of £500 from St. John's College as a contribution to the equipment of the Solar Physics Observatory. The Chair of Astrophysics was partially endowed by an anonymous donor, the offer to become effective on the termination of Newall's tenure of the Chair. The donor made the endowment over to the University in the summer of 1928, Newall retired in the following November.

To return to Newall's published work we may mention a note on the spectrum of the daylight comet 1910 *c*, and a note on bright lines in the spectrum of the Sun's limb at

the partial eclipse of 1912 April 16–17. This flash spectrum of an upper stratum of the reversing layer suggested to Newall that valuable results might be obtained by an observer using instruments of high dispersive power just outside the belt of totality at an eclipse. A similar observation and suggestion were made independently at the same time by A. Fowler.

An expedition to observe the total eclipse of 1914 August 20–21 found the Newalls at Feodosia in the Crimea when the Great War broke out. The programme of observations was along the general lines of Newall's previous expeditions, but cloud prevented any successful observations from being made. He returned to Cambridge to find his observatory with a reduced staff and to be asked to assist in tackling certain war problems for the services. Pure scientific work was compelled to proceed slowly, but he published a preliminary note with F. E. Baxandall and C. P. Butler on the identification of the G band in the Sun with the hydrocarbon band at λ 4314; he also began with W. Moss a study of sunspot areas and life-histories and of zones of prominence activity, while he continued observations on sunspot spectra with the McClean instruments. Later he began, with the aid of his secretary, Mrs. Beech, a study of the frequency of occurrence of groups of sunspots in different solar latitudes. Irregular proper motions were examined in connection with Hale's work on vortical motion. Detailed differences were found with relation to motions in latitude and longitude between the northern and southern hemispheres and related to epochs of frequency maximum. This led to a note to the Society on the "Law of Rotation of the Sun", and later to a study of the different relative motions of pairs of spots in one hemisphere in successive sunspot cycles.

Other papers published were on Nova Geminorum, 1912; Nova Aquilæ, 1918; and Nova Cygni, 1920. His last published paper was with Carroll, Smart and Butler on an expedition to Aal in the Hallingdal, Norway, for the eclipse of 1927 June 29. Bad weather again prevented any observations. The programme of observations showed two developments from the earlier programmes in the use of spectrophotometry for flash and coronal spectra and interferometric measurements for accurate coronal wavelengths and line-widths.

The following year Newall resigned his Chair and his post as Director of the Solar Physics Observatory. His years of retirement were saddened by the death in 1930 of Mrs. Newall, his companion for nearly fifty years. She did not live to attend later in the year the presentation to the University of his portrait by Fiddes Watt, painted at the request of numerous friends and admirers. The portrait is now in the Director's room at the Solar Physics Observatory. Newall married again in 1931 Dame Bertha Surtees Philpotts, sometime mistress of Girton College and a very close friend of his first wife and himself. But she was already stricken with a serious illness when they married and she died in the following year. Newall lived on quietly at Madingley Rise for twelve more years, keeping touch with his circle of friends both in the University and outside, especially with overseas astronomers as opportunity offered for them to visit Cambridge.

There is another aspect of his astronomical work which must be mentioned here, that of international co-operation. He was appointed to represent the Royal Society in 1905 at the Oxford Conference of the International Union for Co-operation in Solar Research: there he was made chairman of a committee on the Investigation of the Spectra of Sunspots, and two years later at Meudon he brought forward a proposal for a committee on Solar Rotation, of which he was made a member. He was chairman of this committee at the Mount Wilson meeting of the Union in 1910, where he proposed that the Union should extend its scope to include the subject of stellar spectra; he was made a member of a committee on Stellar Classification resulting from the adoption of his proposal. At Bonn in 1913, a meeting which he was unable to attend owing to illness, he was further made a member of a committee for photographing features of the solar atmosphere and studying motions in the solar atmosphere other than rotation.

After the Great War Newall attended the foundation meeting of the International Astronomical Union at Brussels in 1919 and was appointed president of the committee on Solar Rotation and member of committees on the Solar Atmosphere (later altered to Solar Physics), Wave-length Tables of Solar Spectral Lines, Nebulæ, Classification of Stellar Spectra. Later he became a member of committees on Radial Velocities and on Sunspot and Solar Characteristic Figures. He had resigned by 1928 from all these committees except those on Solar Physics and Sunspot and Solar Characteristic Figures, in which subjects he retained an active interest to the end. He succeeded Hough as Vice-President of the Union and served on the Executive Committee of the Union at the Cambridge meeting in 1925. The last meeting he attended was in 1928 at Leiden. The growing load that Newall carried during the last working years of his life has been described above. His health was never robust and he was not infrequently laid up for long spells. His delicacy of body was accompanied by a delicacy and diffidence of mind which prevented him from giving out all that was latent in a mind which had the sympathetically inquiring outlook of the genuine naturalist combined with a wide knowledge of experimental physics. In his early days he was a pioneer in spectroscopic design and he never ceased to be actively interested in instrumental developments. Early references to such matters as oscillating slits in spectroheliographs and the importance of the shapes of grooves in gratings in determining the intensities of spectra of different orders are among the items which catch the eye in a re-reading of his papers. Similarly we may note again the early observation of downrushes of hydrogen on the Sun which led him to speculate, in an address to the Society on retiring from the Presidency, that the main characteristics of spectroscopic phenomena of the Sun and stars may be dictated by matter continually streaming in from without. Other glimpses of his outlook, the open outlook of a mind not trammelled by current orthodoxy, are to be found in his reviews of such books as Eddington's *Internal Constitution of the Stars* or Hale's *Study of Stellar Evolution.*

Hale exercised a profound effect on Newall. They had the same wide range of interests outside their chosen pursuit. In Newall's case the most important were a love of flowers and of music. His first wife was a fine pianist and their home became a musical centre of high importance in the life of Cambridge. After her death Newall held a leading position in musical circles in Cambridge. His charming personality and dignified and gracious appearance will remain a cherished memory in the hearts of many friends. His true memorial lies, however, in the Astrophysical Department of the University of Cambridge. This notice of his life has become almost inevitably a story of the growth of the study of astrophysics at Cambridge, a growth fostered by his activities, his leadership and his sympathy with young minds. It would not be unfitting to apply to him in the Solar Physics Observatory, the words used of Wren in St. Paul's Cathedral—*Si monumentum requiris, circumspice.*

He was a foreign member of the Spettroscopisti Italiani and was an Honorary Doctor of Science of Durham University, following in the steps of his father who was an Honorary Doctor of Civil Law of the same University. Newall was President of the Cambridge Philosophical Society, 1914–6.

Elected a Fellow of the Society on 1891 June 12, he served on the Council from 1893 to 1936, being Secretary 1897 to 1901, Vice-President for fourteen years and President for the years 1907–9.

He died at Cambridge on 1944 February 22 at the ripe age of eighty-six.

F. J. M. STRATTON.

JACOBUS CORNELIUS REYNEKE was born in the Free State of South Africa and entered the ministry of the Dutch Reformed Church. After a short stay at Sutherland, he became minister at Cradock and served this church practically all his life; he

spent the few years of his retirement at Wepener and Port Elizabeth, but returned to Cradock to end his days as he said "amongst his friends".

He was an exceptionally good preacher, was interested in mission work and education, serving on the committee of Rocklands Girls High School.

He was keenly interested in astronomy and was said to have at one time possessed the largest and best equipped amateur telescope in the Union.

Throughout his life he enjoyed excellent health and died on 1943 November 20 at the ripe old age of eighty-nine.

He was twice married; his widow, two sons and one daughter survive him.

He was elected a Fellow on 1923 January 12.

WILLIAM SMALLEY, of The Highlands, Crowborough, passed away on 1944 September 16. He was a son of one of the founders of the great Lancashire firm of textile machinists, Tweedales & Smalley, Ltd., of Castleton, near Manchester, retiring from active participation in the business when the present public company took over its affairs shortly after the last war. He was an original Council Member of the Manchester Astronomical Society, acting as librarian of that body for many years and retaining membership long after leaving Lancashire. He was the owner of a fine observatory, housing a 6-inch equatorial refractor, equipped primarily for observation of the Sun, but his business interests, and, in later years, his municipal duties, did not permit of his applying himself to any specific programme of astronomical work beyond that of introducing his fellow-men to the manifold wonders of the sky.

On his retirement from business, seeking health for his ailing wife, Smalley took up residence at The Highlands, a lovely old house in Crowborough, where he became the personal friend of Sir Arthur Conan Doyle, the creator of "Sherlock Holmes". Very soon his shrewd northern outlook was recognized by his new neighbours, and he was quickly elected to the Sussex County Council. In his later years Smalley became President of the Crowborough Golf Club, and during the summer months the Crowborough Bowling Club met weekly, by invitation, on his private green. He was the leader of the local Boy Scouts, whose meetings took place in his coach-house, and served as Chief Air Raid Warden of the Crowborough district.

Physically, Smalley was a handsome and elegant man, generous and helpful, with an intense love of scientific pursuits, and a mechanical ingenuity above the average. He married Miss Heywood, a daughter of one of Manchester's best-known families, who predeceased him by many years. He was sixty-four years of age, and is survived by two of his four sons.

He was elected a Fellow of the Society on 1922 January 13.

WILLIAM PORTHOUSE.

LESLIE WOOLVEN was born at Sutton, Surrey, in 1892 and educated there. He spent more than half his short life in that town until his marriage in 1926. He was a clerical officer in the Ministry of Labour and National Service (Statistics Department) in London, and, when his Department was evacuated to Southport, Woolven went there. In 1944 April he was taken ill very suddenly, and after sixteen weeks of acute suffering in the Southport Hospital he died on August 5, leaving a widow. He served in the Coldstream Guards in the Great War, and was truly proud to have been connected with that famous regiment.

Throughout his life he was a most active worker, but, like most busy people, he could always find time to lend a hand to anyone in need. By nature he was studious and a deep thinker: a keen and devout churchman: and he had the saving grace of wonderful good humour. To the writer he gave the impression of being possessed of a charm of

manner which manifested itself in an old-world courtliness, and one always felt one was in the presence of a true gentleman.

His leisure hours were spent in the indulgence of the self-taught hobby of furniture-making and wood-carving, and his house was furnished very largely with his own handiwork. He helped in the construction of the High Altar at St. Olave's Church, Mitcham, Surrey.

His main interest in our science, after joining the British Astronomical Association in 1923, was in recording the details of sunspots, using a $4\frac{1}{2}$-inch telescope and a magnification giving a 24-inch image for the most important groups and a 6-inch image for the daily positions. His drawings were executed with meticulous care, and, after joining the Solar Section of the British Astronomical Association, he quickly became one of its most assiduous workers, not only on the observational side but also in reducing the results therefrom. Many of his ideas were original, and he has left on record a number of graphs which it is hoped will be published in the future.

He was elected a Fellow of the Society on 1932 June 10.

A. M. NEWBEGIN.

PROCEEDINGS OF OBSERVATORIES

Royal Observatory, Greenwich
(Director, Sir H. Spencer Jones, F.R.S., Astronomer Royal)

Airy Transit Circle.—The restricted programme of observations of the Sun, planets, clock and azimuth stars has been continued. 1666 transits and 1317 zenith distances of stars were obtained; there were, in addition, 205 observations of the Sun, 43 observations of Venus and 22 observations of other planets.

First Greenwich Catalogue of Stars for 1950.—The observations for this catalogue, comprising stars in the zone +0° to +24° declination, extended over the period 1931-40. Final places for equinox 1950 have been derived for all the zone stars and for those in the clock and azimuth lists. The precessions and secular variations have been computed, and the computation of the proper motions of stars not contained in the Albany *General Catalogue* is in progress. For this purpose a detailed comparison between the Greenwich and GC places has been made.

The catalogue positions of stars in the belt of declination +0° to +21° have been communicated in advance of publication to the Director of the Yale University Observatory, for use as reference stars in the reduction of photographs obtained at Yale with the wide-angle lens camera. The reductions for the zones +9° to +20° are in progress at Yale; the discussion for the first twelve hours of R.A. indicates for the probable error of a Greenwich catalogue position at the epoch of the Yale plates (1940·0) a value between 0″·145 and 0″·150, in satisfactory agreement with the probable error at the mean epoch of observation of 0″·14, derived at Greenwich from the accordance of the individual observations.

Reversible Transit Circle.—Two papers, giving an account of the preliminary results of the tests and observations made with the instrument until they were suspended towards the end of 1940 and of the determination of the division errors of the fixed circle, have been published in the *Monthly Notices.*

Cookson Zenith Telescope.—The observations made from 1936 July until 1940 September, when the instrument was partially dismantled, have been reduced and the variation of latitude derived. The results have been communicated to the Society. Investigations into the cause of occasional discordant results, suspected to be due to anomalous surface tension effects, have been carried out, but no definite conclusions were reached.

Photographic Zenith Tube.—The construction of a photographic zenith tube, to serve the double purpose of the accurate determination both of time and of latitude variation, has been approved by the Admiralty. Much thought has been given to the details of the design, which will be a considerably modified version of that of the photographic zenith tube in the U.S. Naval Observatory, Washington. The main details of the design, which is on kinematical principles, have been settled and construction is now proceeding.

Horizontal Transit Instrument.—A new type of transit instrument has been designed which should enable time to be determined with a much higher accuracy than the conventional type of small transit instrument. The principal cause of error in observations with the small transit instrument arises from the difficulty of determining the level error and its variations with sufficient accuracy. In the new instrument, the telescope system remains fixed (though adjustable) with its axis horizontal and in the east-west direction. The light from a star of any declination, near the position of meridian transit, is directed along the optic axis by a subsidiary optical system, which can be rotated about an east-west axis and can be set to the appropriate declination. The effect on time determination

of its positional errors (whether due to maladjustment of the axis of rotation or to pivotal errors) is reduced to the second order. An investigation of the theoretical aspects of the system has been made, and in order to try the system out in practice the construction of an experimental instrument is at present in progress.

Thompson Equatorial.—325 plates have been measured for the determination of parallax. The measurement of plates obtained before observations were discontinued in 1940 has now been concluded until the instrument can be brought back into use and further photographs obtained.

Photoheliograph.—Photographs of the Sun were obtained on 253 days in 1943 and on 250 days in 1944. In the combined series (Greenwich, Cape and Kodaikanal Observatories) two days in 1943 and one day in 1944 are unrepresented. 623 Greenwich plates have been measured. The copy for press of the Daily Results has been prepared to the end of 1943 from the Greenwich plates. On the outbreak of hostilities, H.M. Astronomer at the Cape was instructed to retain the Cape plates, because of the risk of loss in transit. The Cape plates required to fill the gaps in the Greenwich series for the years 1939 and 1940 have been packed ready for shipment.

The computations of positions and areas of sunspots have been continued from the Greenwich plates and have been completed up to 1944 December 28.

Daily sunspot numbers, based on Wolf's method of counting, have been sent to Professor Brunner at Zürich, for incorporation in the I.A.U. Solar Bulletins.

Sunspot frequency indicates that the Sun passed through the minimum of activity shortly before the middle of 1944. Sunspots in high latitudes (20°–35°) are becoming increasingly frequent. The largest spot-group, just exceeding 1000 millionths, crossed the Sun's disk between 1944 December 8 and 20, in south latitude 22°. A "great" magnetic storm was recorded at Abinger on 1944 December 16.

Spectrohelioscope.—The instrument was used on 311 days in the two years. The frequency of observable phenomena in *Hα* has fallen considerably, though the year 1944 showed some increase as compared with the year 1943. Measures have been made of line-of-sight velocities of bright and dark flocculi and of equivalent line-widths of *Hα*. Photometric measures of patches of bright flocculi and measures of line-of-sight motions in prominences have also been made. Lists of observed solar flares have been sent to Professor Brunner quarterly. Ionospheric data are received monthly from the Radio Research Station, Slough, and details of radio fade-outs are supplied by Cable and Wireless Ltd. and the British Broadcasting Corporation.

Time Service.—The time service has been maintained from the two stations at the Abinger Magnetic Observatory and at the Royal Observatory, Edinburgh. Each station has been available for sending out the Rugby signals, the B.B.C. six-pips time-signals and the hourly signals to the Post Office for the control of the speaking clock and other services. The Rugby time-signals at 10^h daily, which are used for the checking of precision frequency standards and for which the highest possible accuracy is required, have normally been sent from Edinburgh, because the line conditions from Edinburgh to the Rugby radio transmitting station have been more stable than those from Abinger. The improvement of the line conditions between Abinger and Rugby is under discussion with the Post Office Telegraph Branch. The B.B.C. six-pips time-signals are normally sent from Abinger.

The two stations are interconnected by land line with teleprinter communication at each end. Signals from the clocks at either station can be recorded at the other station. The lag of the interstation line is determined by looping the line and sending a signal round the loop.

Stellar observations for the determination of time are made at both stations: at Abinger with a small reversible transit circle and at Edinburgh with the reversible transit circle. The observations are combined for the determination of the clock errors at the two stations. 535 separate determinations of time have been made in two years.

Progress in the installation of the new quartz clocks has been slow. Three of these have been in use: A^1 at Edinburgh and B^1 and B^2 at Abinger. These are still mains operated. Momentary flickering on the electric mains supply or complete interruption of the supply, as the result of flying-bomb and rocket attacks, have caused frequent stoppage of the Abinger clocks. It is hoped soon to transfer the Abinger clocks to battery operation, when they will be free from mains troubles. The time has therefore again been based mainly on quartz standards in establishments outside the observatory, of which the clock IVC at the Post Office Radio Branch Laboratories has proved to be the best. The transit observations have been used to determine the general run of the Post Office clocks. The prediction line is then transferred to A^1, which has been adopted as the secondary standard. A^1 is used to control the 10^h signals. The predictions on A^1 are transferred to B^2, so that B^2 can be set to time to provide an alternative signal from Abinger, in the event of signals from Edinburgh failing for any reason to reach the Rugby station. B^2 also controls the 18^h signals.

Foreign time-signals, including French, German, Russian and American signals, have been received. A large number of receptions of the WWV signals from the National Bureau of Standards, Washington, have been recorded with the aid of the decimal counter chronometer.

Much development work, directed to the improvement in the accuracy of the time service and in the accuracy of reception of time-signals, has been undertaken at Abinger. Details will be found in the Reports of the Astronomer Royal to the Board of Visitors of the Royal Observatory, Greenwich.

Nautical Almanac Office.—During the two years under review the astronomical work of the Office has been reduced to the minimum compatible with the production of the *Nautical Almanac* and other ephemerides. The computational experience of the Office has been put to good purpose on non-astronomical problems and has largely formed the basis of the Admiralty Computing Service; for this purpose the staff has been considerably increased. Although the computing work undertaken is general in character, it is remarkable how many investigations have involved the specialised knowledge of spherical trigonometry and its numerical treatment which is the basis of astronomical and navigational computation.

Since 1943 January 1 the following publications have been issued or completed except for final printing:—

Publication	*Published (or to be published)*
Nautical Almanac, 1944	May, 1943.
Nautical Almanac, 1945	March, 1944.
Nautical Almanac, 1946	(March, 1945).
Abridged Nautical Almanac, 1944	February, 1943.
Abridged Nautical Almanac, 1945	March, 1944.
Abridged Nautical Almanac, 1946	(March, 1945).
Apparent Places of Fundamental Stars, 1944	May, 1943.
Apparent Places of Fundamental Stars, 1945	June, 1944.
Apparent Places of Fundamental Stars, 1946	(May, 1945.)
Air Almanac, 3rd part, 1943, to 2nd part, 1945	About 6 months in advance.

A fifteenth volume of *Astronomical Navigation Tables* has been issued, to cover latitudes 70°–79°, the star portion being confined to North latitudes.

In addition, many special publications of astronomical or navigational data have been prepared for particular or general purposes. One of these, "Tables for the Depression and Azimuth of the Sun" for latitudes N. 45° to N. 60°, will shortly be distributed as an Office publication; it gives a comprehensive table of the depression of the Sun below the horizon between the limits 6° and 18°, and will be found a better guide for astronomical observations than the twilight tables in the *Nautical Almanac*.

Preliminary stages in the preparation of the *Nautical Almanac* are suitably performed

several years at a time by the use of punched card equipment. The noon and midnight values of the Moon's longitude, latitude and parallax have been computed from Brown's *Tables of the Motion of the Moon*, and the main stage of the conversion of these values to corresponding values of the right ascension and declination has been completed for the years 1951–60. For the same years, midnight values of the heliocentric equatorial rectangular co-ordinates of Mercury and Venus have been obtained from the heliocentric latitude, longitude and radius vector which were already available from Newcomb's *Tables*. Apart from the final stages of conversion to apparent position, which is done year by year as required, the whole of the fundamental work on the Sun, Moon and planets is thus complete to 1960. It is hoped shortly to complete all punched card processes for the Moon's longitude, latitude and parallax to the year 2000.

No changes have been made in the *Nautical Almanac*, which is still much reduced in size in comparison with the edition for 1941. Preparation of the *Supplement* is in progress, and a general revision of the *Almanac* is under consideration.

For the years 1944, 1945 and 1946, the apparent places of the 426 10-day stars normally received from the Office of the *Connaissance des Temps* for inclusion in the volume of *Apparent Places of Fundamental Stars* were computed in the Office, while the 32 circumpolar stars for the years 1945 and 1946 were received from the Office of the *American Ephemeris*. The French, German and Spanish introductions to this volume are being reinserted in the 1946 edition.

The reopening of communications will enable France to supply once again the calculations allotted under international agreement, which have during the war been jointly undertaken by Britain and America.

The scope of the occultation prediction programme has been increased as enemy-occupied countries have been liberated. Predictions of occultations for 1945 and 1946 have been dispatched to all observatories so far liberated. Partially reduced observations have been received for 1943 and 1944, somewhat irregularly due to war-time difficulties of communication. Reductions received for 1943 have mostly been completed, but further observations are expected. Plans for centralised publication have been delayed and no definite scheme is yet in operation.

By agreement with Professor Brouwer, the annual discussion of the motion of the Moon derived from observations of occultations will, as from 1943, be undertaken by the Royal Observatory; it is hoped to continue a preliminary investigation, started before the war, into the practicability of taking account of the irregularities in the limb of the Moon.

Although little change has been made in the form or presentation of the navigational publications issued by the Office, much investigatory work has been undertaken, particularly for the Air Ministry, into various instrumental, tabular and graphical methods for astronomical navigation. In several cases sufficient calculations have been made to allow of a full-scale test of the methods. The annual visits to the Office of the R.A.F. Specialist Navigation Course have provided many opportunities for the interchange of practical and theoretical view-points.

Royal Observatory, Edinburgh

(*Director, Professor W. M. H. Greaves, F.R.S., Astronomer Royal for Scotland*)

This report covers the period 1940 December to 1945 April.

In the autumn of 1940, as a result of representations made by the Astronomer Royal, it was decided that the Observatory should be equipped for the purpose of duplicating the various time signals normally originating from Greenwich. (Provision had previously been made for transmitting the B.B.C. "six-pips" signals only.) The work of installation was to a large extent carried through in 1940 December, the equipment sent from Green-

wich including the Free Pendulum Clocks Shortt Nos. 11 and 16. By the end of December the work of installation had fortunately been carried to a point which allowed the transmission of rhythmic signals to Rugby, and as a result the Observatory was able to operate the Rugby signals, although under difficult conditions, in 1941 January when, in consequence of enemy action, it was impossible to operate this service from the Greenwich station at Abinger. At the same time the work of installation proceeded. From 1941 May to 1943 March 29 and from 1943 October 27 to the present date the rhythmic signals radiated from Rugby at 10^h U.T. were normally operated from Edinburgh, but originated from Abinger on a few occasions when, owing to technical faults, transmissions from Edinburgh were not possible or advisable. A large number of the Rugby transmissions at 18^h U.T. and of the transmissions from British short-wave stations (which were commenced in 1942 July) have also been operated from Edinburgh. On a few occasions the Observatory has been called upon to operate the B.B.C. "six-pips" signals. Hourly signals to the Post Office have been supplied and have been available for the control of the "speaking clock".

In 1943 February a direct line link was installed between Abinger and Edinburgh whereby the clocks at each station were made available at the other. Early in 1944 a quartz clock of the Post Office Group IV type, the first of a set of such clocks constructed for the Royal Observatory, Greenwich, by the Post Office Radio Branch Laboratories, was installed at Edinburgh, and commencing 1944 February 26 the Rugby signals both at 10^h and 18^h U.T. (at the time the 18^h signals were being operated from Edinburgh) originated from this clock, the phonic motor of which was constructed so as to provide for the transmission of rhythmic vernier signals. A similar clock was installed at Abinger shortly afterwards (together with another Group IV clock, the phonic motor of which delivers mean time second impulses).

Throughout the whole period transit observations were secured at Edinburgh on all possible occasions, and were combined with observations obtained at Abinger for the purpose of deriving clock errors.

Considerable developments have been made in the general technique of the Time Service during these war years. In the following paragraphs reference will be made only to development work carried out at Edinburgh with the object of improving the service. This report is thus to be regarded as supplementary to the Greenwich reports, to which reference must be made for a complete account of the various changes that have been made in the pre-war technique. In addition to the requirement of providing signals giving absolute time to an accuracy adequate for navigational and surveying purposes, the signals radiated from Rugby at 10^h U.T. are now intended to provide a standard of frequency, the desideratum being that consecutive 10^h signals should define an interval of 24 hours with an accuracy of the order of a millisecond. The development work which has been carried out at the Edinburgh end has been concentrated on this aspect of the service.

Throughout the years 1941 to 1943 the operation of the service was based on Shortt free pendulum clocks. During this period the performance was improved. The original circuit arrangements were modified, and in addition to the development (to which reference is made below) of line transmission, radio reception and chronographic measurement, a technique was developed for using a "mean clock" for signal transmission purposes, the effect of clock erratics being reduced by averaging as many clocks as were available. The process developed was similar in principle to the process previously developed at Greenwich for the purpose of basing definitive corrections to the signals on a "mean clock", but there were differences in detail which arose from the circumstance that for signal transmission purposes clock errors have to be extrapolated. During 1942 a fundamental change was made in that the service was ultimately based on quartz controlled clocks situated at other institutions, and the process of extrapolation of the errors of the pendulum clocks at the Observatory was reduced to extrapolations, for periods of

24 hours only, of the relative errors of the pendulum clocks and the quartz controlled standards, these relative errors being obtained *via* a radio link which employed the 10^h Rugby signals themselves. It had become apparent at this stage that the performance of quartz controlled clocks was of an altogether higher order than that of the best pendulum clocks. During 1942 and 1943 some investigations were carried out on the erratics of free-pendulum and quartz clocks, the results being published in a paper by Greaves and Symms (*M.N.*, **103**, 196—the free-pendulum clocks designated X, Y and Z in this paper are respectively Shortt 4, Shortt 11 and Shortt 16). The conclusion reached that the P.O. type quartz controlled clocks are very superior in performance has been more than confirmed by subsequent experience. As regards their erratics of rate (designated in the paper by types B and C) the mean absolute scatter in daily rates has been found (from an analysis, made at the Observatory, of the results of beat frequency comparisons supplied by the Post Office Radio Branch Laboratories) to be of the order of $\pm 0{\cdot}05$ milliseconds per day. This figure represents a combination of erratics of types B and C, and the performance indicated thereby contrasts strikingly with that of the Shortt clocks for which the mean absolute scatter of daily rate due to type C erratics alone seems to be of the order of ± 1 to ± 2 milliseconds per day. The "wanderings" of pendulum clocks are in fact much greater than those of quartz controlled clocks of the Post Office Group IV type. As regards erratics of type A, an investigation, using an electronic chronometer, at the Post Office Radio Branch Laboratories has shown that the phonic motors of the quartz clocks introduce random errors with a standard deviation of the order of $\pm 0{\cdot}1$ milliseconds. The Observatory is indebted to the Radio Branch, Engineer-in-Chief's Office, General Post Office, for permission to quote this result and the result of the analysis of the beat frequency comparisons.

It was clear that the state of affairs in which the signals were operated by pendulum clocks was unsatisfactory, even though the service was ultimately based on quartz controlled clocks. But in some respects the experience gained with pendulum clocks was of permanent value. The performance of the "mean" pendulum clock was good enough to justify efforts being made to reduce the errors of radio reception and chronographic measurement and to secure a greater degree of constancy of the transmission time over the line system connecting the Observatory to Rugby. The technique of radio reception and of chronographic measurement were developed and, largely owing to the very valuable co-operation given by the Post Office Engineering Department (Scottish Region), considerable reductions were effected in the errors introduced by variable line lag. The result was that when the quartz clock was installed in 1944 it was possible to take advantage of its superiority and to reduce materially the errors of individual 24-hour intervals defined by consecutive G.B.R. signals at 10^h. But it became clear that the full superiority of the clock was not being utilised. More improvements were made in the chronographic technique, and in the later months of 1944 efforts were successfully made to secure a further reduction of errors due to line transmission. A series of experiments, which included oscillographic investigations of build-up, were carried out with a view to improving the method whereby the signals are fed on to the line, and the previous circuit arrangements were modified. The Post Office contributed to this by supplying relays of a greatly improved type, and they took the important step of discarding the arrangement whereby a traffic line channel was switched over to signal use for a short period only, and provided a permanent channel, with a loop at Rugby feeding a return channel, and available for test at any time. This channel became available in 1945 January; an arrangement was made whereby the stability of the line system was kept under observation at the Observatory, and on receipt of a message that re-adjustment of the system was necessary the Post Office engineering staffs have promptly taken the necessary steps. In addition they have themselves made regular tests of line stability, employing the same method of testing as has been applied at the Observatory. This method is an adaptation of the "chaser" method devised at Greenwich for measuring the total lag of a looped

line. In the adaptation a meter reading indicates whether the line system is in good adjustment.

In 1945 March arrangements were made whereby a test signal is sent out from the Observatory and radiated by Rugby at $9^h\ 30^m$ U.T. on each day, a direct measure of lag being thus made half an hour prior to the signal at 10^h U.T. As a result of the improved stability of the line itself (mainly due to the stringent control), of the improved method of feeding signals on to it, and of the provision for direct measurement of the lag at $9^h\ 30^m$ U.T., the standard deviation of the measured errors of individual intervals of 24 hours has been reduced to $\pm 0{\cdot}6$ milliseconds (the mean absolute scatter being $\pm 0{\cdot}5$). This figure represents errors which are additive to the errors in the 24-hour intervals introduced by the general trend of the signals. It is the practice to adopt a parabolic arc on the plot of clock errors against date, and to base the signal transmissions on this adoption. The adopted curve is revised from time to time as further transit observations become available, attention being paid to the comparisons of the signal transmitting clock with other quartz standards. The revisions are not made daily, but a single adoption is used for a period which may extend over several weeks, and consequently the resulting errors in signal rate persist at the same value over extended periods. These are the errors of general trend. From a preliminary discussion covering the period 1944 August 1 to 1945 April 17 their mean absolute value was $\pm 0{\cdot}6$ milliseconds per day with extreme values of $+1{\cdot}5$ and $-2{\cdot}3$. The extremes are larger than one would like, and are due partly to the limitations of the present method of observing transits and partly to the circumstance that the Observatory clock is mains operated, the crystal frequency being liable to disturbance from surges and failures of mains voltage. There is no doubt that these errors of general trend could be diminished by the provision of better types of transit instrument, and by the provision of battery drive for the quartz clock. As regards the additional errors in individual intervals of 24 hours, part of the measured mean absolute scatter of $\pm 0{\cdot}5$ milliseconds quoted above is certainly due to errors of radio reception and of chronographic measurement, and the real signal performance must be better than is indicated by this figure. The precautions which have been taken include the reduction of the errors of radio reception by oscillographic control of the tuning and of the output voltage of the receiver, and the technique of chronographic measurement has been refined as far as possible. It is felt that there is little chance of reducing the errors of reception and measurement still further as long as classical chronographic methods are employed. In fact, as has been indicated, some considerable effort was expended in the achievement of the standard of accuracy that has actually been reached, and the same remark applies to recent signal performance which has been the result of close co-operation between the Observatory and the Post Office Engineering Department (Scottish Region). The reduction of the errors introduced by line transmission to the level indicated by the measured mean absolute scatter of $\pm 0{\cdot}5$ milliseconds for individual 24-hour intervals is regarded as very satisfactory.

It is now expected that the participation of the Observatory in the Greenwich Time Service will soon be terminated, and that a resumption of pre-war activities will be possible. Some preliminary work connected with the resumption of the spectrophotometric programme of the measurement of line intensities in stars of types O and B has recently been done, and it is hoped to get the full programme re-started at an early date.

Royal Observatory, Cape of Good Hope
(Director, Dr. J. Jackson, F.R.S., H.M. Astronomer)

Reversible Transit Circle.—The observation of the Boss and Backlund-Hough stars south of declination $+35°$ begun in 1936 was brought to a close in 1944 May. The great majority of the 5373 stars were observed 5 times in each of two positions of the instrument. The formation of a catalogue based on these observations is well in hand, all the observations having been reduced to mean place for 1940·0 before a final reduction to 1950·0.

The right ascensions have been reduced to the system of FK3. An analysis of the difference between the day and night observations indicates the following correction to the FK3 system:—

$$+^{s}.0006 \cos \alpha - ^{s}.0022 \sin \alpha + ^{s}.0039 \cos 2\alpha - ^{s}.0073 \sin 2\alpha.$$

The coefficients are smaller than those for previous fundamental catalogues, and are of the same order as their probable errors which are greater for the second harmonic terms.

The instrument was completely overhauled in 1944 May and June, and the errors of the pivots and of the micrometer screws were investigated. The pivot errors found in 1938 and 1940 were closely confirmed—they have increased from the values when the instrument was new. The micrometer screws have worn considerably, but as the opposite micrometers are reversed the effect on the mean of the six microscope readings is negligible.

As only two observers were available, a less ambitious new programme was started in 1944 July. It consists of 2611 stars mainly of the 8th and 9th magnitudes between declinations $-56°$ and $-64°$. These stars will serve as standard stars for photographic plates in the zone $-56°$ to $-60°$ and $-60°$ to $-64°$. The observations will be standardised by means of 483 stars of the GC in the zone, reduced to the FK3 system by the application of systematic corrections. A reversing prism is being used and also screens to cut down the brighter stars to about the 8th magnitude.

Day observations were carried out as far as possible. Observations of the Sun, Moon and planets were obtained as follows:—

Sun	247	Ceres	6	Mars	15
Moon	103	Pallos	13	Jupiter	30
Mercury	139	Juno	10	Saturn	23
Venus	205	Vesta	10	Uranus	25
				Neptune	23

Victoria Telescope.—In the two years 4353 plates were exposed for parallax determinations: 4367 plates were measured and nearly 7000 remain to be measured. The parallaxes of 124 stars were determined for the first time, bringing the total since the programme started in 1926 to 1379.

The programme now includes a considerable number of stars observed early in the work and being re-observed on account of the large parallax or because of the weakness of the original series of observations. There is naturally a tendency in this work to observe the most important stars first and to publish results from a minimum of material. For both reasons many stars should be re-observed. New stars added to the programme have mostly been faint stars with a proper motion of more than $0''.5$ discovered by Luyten, or stars with proper motion of $0''.2$ to $0''.3$ from the *General Catalogue* for those hours of R.A. where there are few other suitable stars to observe.

Photometry.—The measurement of the 12,800 stars in the zone $-30°$ to $-35°$ has been completed, and the resulting photographic and photovisual magnitudes have been reduced to the present standard Cape system by the application of colour and scale correction. At the same time zero-point corrections derived from an investigation of the plate overlaps were applied. Great difficulty has been met in attempting to reduce the magnitudes to the International System. The magnitudes available for the Standard E regions at $-45°$, the Hyades and Præsepe Clusters and the Eros Comparison Stars, have not proved as accurate or as consistent as required. Two papers dealing with these difficulties have been sent to the Society.

Early in 1944, Dr. Redman of the Radcliffe Observatory offered to co-operate in the observation of the zone $-35°$ to $-40°$. This offer was gratefully accepted, and the photometric cameras were sent to Pretoria, where they were mounted on the tube of the

74-inch reflector. Routine observing began at the end of June and is now almost finished. Routine measurement of the plates began in August.

For the $-35°$ to $-40°$ zone the magnitudes are being determined by straight comparison with the Standard E regions at $-45°$. Two sets of plates are being used; the one set has a series of 15-minute exposures, the other a series of 3-minute exposures. At the same time a series of plates with 15-minute exposures intercomparing the E regions with one another and with the Hyades and Præsepe is being obtained. The purpose of these latter plates is to improve the magnitudes of the fainter stars in the E region sequences and to provide the material for reducing the zone magnitudes to a standard system.

The measures indicate that the plates taken in Pretoria are superior to those taken at the Cape. The improvement is more marked for the photographic magnitudes. It can be attributed partly to the superior climatic conditions at Pretoria and partly to the great trouble taken to expose plates only under the best conditions—generally after midnight—and special precautions taken in developing the plates.

A considerable amount of time has been devoted to examining the relations between the photographic magnitudes given in the two Cape Astrographic Zone Catalogues and those given by Harvard for stars in the twenty-four Kapteyn areas at $-45°$. The results so far have been largely negative, due to large irregular fluctuations in the differences between the magnitudes. These irregular fluctuations seem to be quite as much due to Harvard as to the Cape. One point of interest that has emerged is an apparent systematic difference in scale between the magnitudes in the Cape "Bright" and "Faint" Star Catalogues. This difference appears to have its origin in a selection effect, and is due to the CPD magnitudes which were used as the criterion for inclusion in the catalogues and which also enter into the finally adopted Cape photographic magnitudes. These Cape magnitudes are a complicated function of diameter measures made on the Astrographic and CPD plates combined with visual magnitudes corrected by assumed mean colour indices. The only hope of progress seems to lie in an investigation of the properties of each of the contributing measured quantities. In this connection all CPD stars 9·9 and brighter in areas 4° by 6° surrounding eight of the Standard E regions at $-45°$ have been measured. The resulting magnitudes are also being used to make a selection with due regard to colour of standard stars to supplement—or replace—those used at present.

Photoheliograph.—The Sun was photographed on 330 days in 1943 and on 335 days in 1944. As solar activity was low only one plate was generally taken on days during the European summer. The zero of position-angle was determined at regular intervals both visually and photographically.

Occultations.—As in previous years an attempt was made to observe all occultations predicted in the *Nautical Almanac*. 62 observations of 44 phenomena were secured in 1943, and 103 of 54 phenomena in 1944. These observations, as well as 25 made by Mr. H. E. Krumm at Cape Town and 17 by Mr. A. W. J. Cousins at Durban, have been forwarded to the Nautical Almanac Office for discussion.

Eros.—All the suitable images of this minor planet shown on the plates taken in 1938 and 1942 were measured and the results have been published. There were in all the following number of images:—

Opposition of 1938: 23 images on 8 plates taken with the Astrographic telescope.
Opposition of 1942: 54 images on 18 plates taken with the Astrographic telescope west of the pier, and 51 on 18 plates east of the pier.
89 images on 16 plates taken with the Victoria telescope.

The observations for 1942 are in very close agreement with the accurate ephemeris published in *Astronomische Nachrichten*.

Comets.—The only comet observed was that discovered by Dr. van Gent at Johannesburg in 1943 November. For the use of South African observers orbits of this comet

were computed, and also of the comets discovered by Dr. van Gent and Mr. du Toit of Bloemfontein in 1944.

Friendly assistance has been given by astronomers both professional and amateur in South Africa. Besides the photometric work already mentioned which is being done at Pretoria, Dr. G. G. Cillié, jnr., at Stellenbosch, has been determining spectral types for the zone $-30°$ to $-35°$ from plates taken at the Southern Station of the Harvard Observatory at Bloemfontein. At the observatory itself Mr. H. C. Davies has specialised in the observation of occultations and Mr. W. P. Hirst has measured double stars with the 7-inch refractor. Mr. de Kock is making increasing use of the 6-inch refractor for the observation of variable stars.

Armagh Observatory
(*Director, Dr. E. M. Lindsay*)

The Director has been on leave of absence. The routine meteorological work has been continued. The 10-inch refractor has been used by Mr. Hutchings for observations of occultations and of long-period variables.

Cambridge Observatory
(*Acting Director, Dr. H. A. Brück*)

The year 1944 will always be remembered by the irreparable loss which the Observatory suffered in the untimely death of its Director, Professor Sir Arthur S. Eddington, who died on November 22. The Observatory was unfortunate also in losing the services of Mr. H. E. Green, who died on 1944 September 18 after having been Second Assistant for twenty-six years. On 1943 October 1 Dr. H. A. Brück was appointed John Couch Adams Astronomer.

The principal research was carried out with the new photo-electric photometer attached to the Sheepshanks telescope, reference to which was made in the last report. The sensitivity of the instrument has been improved, so that it is now possible to determine with an accuracy of one per cent. the brightness of an early-type star of magnitude 7. Among objects observed with the photometer were 12 Lacr, RT Auri, δ UMaj and the planet Uranus. Comparisons of this planet with a star should make it possible to test variations of the solar constant by a method which is independent of disturbing factors due to the terrestrial atmosphere.

The correlation between the Harvard and Potsdam systems of spectral classification has been investigated.

Solar Physics Observatory, Cambridge University
(*Deputy Director, Mr. W. Moss*)

The chief programme of observations was devoted to the determination of intensities of the lines hydrogen *Hα* and helium D_3 in the spectra of prominences. The observations were carried out with the spectroheliograph. The photometric reduction of the plates shows the effect of self-absorption in the case of *Hα*, and appears to indicate that intensities of this line when plotted against corresponding intensities of D_3 are generally consistent with a theoretical curve of growth which is based on the assumption of pure thermal Doppler broadening at a temperature of 5000° without any additional effect of possible turbulence. Preliminary results on 9 prominences have been published in the *Monthly Notices*. A further investigation of 25 prominences has been completed.

The distribution of intensity within the inner corona has been studied, and the results have been published in the *Monthly Notices*.

Some more photometric records of the solar spectrum with the photo-electric photo-

meter attached to the McClean solar telescope have been obtained during the summer of 1943.

Records of the solar spectrum in the infra-red region, covering the range from the visible to $\lambda = 14\mu$, have been secured with a rock-salt prism spectrometer. The evidence for the presence of nitrous oxide in the Earth's atmosphere is being re-examined critically.

University Observatory, Glasgow
(*Director, Professor W. M. Smart*)

Work on the proper motions of the *General Catalogue* has been continued; the analysis of the proper motions of stars of types F to K, taken together, into the two constituent drifts for each of the regions of the sky, and a similar analysis for each of the F and K types, have been completed.

A beginning has been made on the analysis of the proper motions of the faint stars in the *Cape Catalogue* of 20,554 faint stars in the zone $-40°$ to $-52°$.

University Observatory, Oxford
(*Director, Professor H. H. Plaskett*)

The astronomical staff of the Observatory were engaged on war-work in 1943 and the greater part of 1944. The Director was released for a resumption of his university duties in 1944 October, while Dr. Adam's release is pending. The solar telescope and spectroscope are being brought back into service, and it is hoped that investigations on limb-effect and on darkening to the limb may be commenced in the spring.

University Observatory, St. Andrews
(*Director, Dr. E. Finlay-Freundlich*)

There has been no change in the staff of the Observatory. The transit instrument has been equipped with an impersonal micrometer and a writing recorder was brought into operation. No routine observational programmes have been begun.

Norman Lockyer Observatory, Sidmouth
(*Director, Mr. D. L. Edwards*)

Work has been continued on the rather reduced scale mentioned in a previous report. Mr. D. R. Barber, since completing his year as Martin Kellog Fellow at the Lick Observatory, has been absent on work of national importance.

In the photographic survey of galactic clusters the results for 23 more clusters have been completed (making 36 in all) and a special analysis made of the group of 19 clusters in Cassiopeia. Theoretical work on problems connected with this survey (particularly on interstellar absorption) has also been continued.

Gradients and colour temperatures of γ Cassiopeiæ have been measured from objective prism spectra of γ and δ Cassiopeiæ. The results cover the period 1938 June to 1941 October. An analysis of all available observations of this star during the past 100 years has also been made. It indicates the existence of changes (both in magnitude and spectrum) throughout this period, with the possibility of regularly recurrent outbursts.

Four papers on galactic clusters and two on γ Cassiopeiæ have been communicated to the Society.

A Hope-Jones Synchronome clock has been presented to the Observatory by Mr. H. O. Short. Much equipment and apparatus has also been received from the estate of the late Lady Lockyer, including a 6-inch Cooke refractor on a clock-driven equatorial mounting.

Stonyhurst College Observatory, near Blackburn
(Director, Rev. J. P. Rowland, S.J.)

The usual routine work of the Observatory has been carried on throughout the two years. The Rev. Father B. G. Swindells, S.J., B.Sc., joined the staff as a part-time assistant in 1943 September, and Mr. W. Brown, our general assistant, was called up for the Forces at the end of that year.

The only astronomical work has been the routine observation of the Sun and measurement of sunspots, which is done by Father Swindells. The number of new groups observed was 60 in 1943 and 38 in 1944. The longest period in which no spots were observed was from 1944 March 30 to May 28, which accordingly appears to be the time of sunspot minimum.

Dominion Astrophysical Observatory, Victoria, B.C.
(Director, Dr. J. A. Pearce)

War-Work.—During the past three years all members of the staff have made contributions to the war effort in Canada. Dr. C. S. Beals, Gas Officer for British Columbia, devoted much time to Civil Defence measures, assisted by Dr. R. M. Petrie. Dr. A. McKellar and Dr. K. O. Wright were on leave of absence for one year giving instruction to army officers at the University of British Columbia. Mr. W. H. Stilwell assisted the Geodetic Service in their survey of new air-fields in the Hudson's Bay area. The Director held a position of instructor in the Royal Canadian Artillery.

Observations.—While the astronomical work of the Observatory has been greatly reduced, observations with the 73-inch reflector have been maintained at normal efficiency. The yearly average shows that 1229 spectra were secured in 1114 observing hours on 180 nights. This is some 9 per cent. below the 25-year average, due almost entirely to adverse observing conditions.

Instruments.—The instrumental resources of the Observatory have been greatly developed. The 84-inch aluminizing chamber was completed in 1943, and the 73-inch primary and 20-inch secondary mirrors successfully aluminized by Dr. McKellar. Tested with a photo-electric reflectometer, the reflectivity of the coat at λ 3900 was 82·6 per cent. as compared with 65 per cent. for freshly deposited silver. A gain of one stellar magnitude has been achieved, and spectra of the 11th magnitude may now be obtained in reasonable time.

Dr. C. S. Beals completed the modification of the three-prism spectrograph from a Universal to a Littrow form designed to make use of either prisms or gratings. Tests for flexure of the cantilever member, which formerly carried the slit assembly but which now carries the cameras as well, indicated that the amount is satisfactorily small. The new instrument has exceeded expectations in its performance, particularly with the two aluminum-on-glass gratings ruled by R. W. Wood. Dispersions of the 1st, 2nd and 3rd orders are 15, 7 and 4·5 A./mm. respectively. Eight inches of the spectrum is photographed at one exposure, and stars of the 5th magnitude have been observed with the highest dispersion.

The two-prism Hilger ultra-violet spectrograph formerly used at the prime focus of the 73-inch telescope has been rebuilt and mounted at the Cassegrain focus. This instrument has a dispersion of 99 A./mm. at λ 3933, and has been chiefly employed as a slitless spectrograph for the investigation of the colour temperatures of early-type stars.

Studies of Emission-Line Stars.—Studies of the P Cygni and Wolf-Rayet stars have been continued by Beals; for the most part in the ordinary and visual regions, although a special investigation of the ultra-violet spectra of Wolf-Rayet stars has recently been undertaken. The results have included a study of the physical nature of the Wolf-Rayet binary HD 193576, reported in these publications (*M.N.*, **104**, 206, 1944), in which it was

shown that the peculiarities of the system were probably due to the W envelope, the diameter of which was of the order of 30 times that of the star. An investigation of the complex P Cygni star MWC 374 showed that the displaced absorption lines had their origin mainly in a region outside the emitting shell, and a reasonable explanation was found for the redward displacement of the emission lines.

Photometric Observations.—The photometer was used on 47 nights, 1100 observations being secured, thus bringing to completion the observations of the photo-electric colour indices of the 250 O- and B-type stars for which gradients had been determined by the Greenwich observers.

Investigations of O- and B-type Stars.—A study of the gradients of faint early-type stars, for the purpose of investigating space absorption, was commenced. Over 500 spectra of 6th to 8th magnitude stars were secured with the slitless ultra-violet spectrograph, and it is proposed eventually to extend the programme to stars of the 10th to 11th magnitude. Gradients were determined from 300 spectra of 8 Wolf-Rayet and 12 Class B stars in Cygnus by Dr. Wm. Petrie, the measurements being made in four spectral regions between $\lambda\lambda$ 6400 – 3400. Spectral line intensities of the principal absorption features in 16 O-type stars were determined by Dr. R. M. Petrie. Useful ratios were found in the lines of neutral and ionized helium for the purpose of spectral classification. A study of the Stark effect of helium was made by Miss A. B. Underhill. Measures of equivalent widths for the *He*I diffuse series in the spectra of three giants and three dwarf B stars indicated a decided weakening of the lines in the spectra of the dwarf stars.

Studies of Cometary Spectra.—Detailed analysis of the spectra of Comet Cunningham, 1940 *c* and Whipple-Fedtke-Tevzadke, 1942 *g*, were made by McKellar. The spectrograms were obtained with relatively high spectral purity with the result that the R branch of the λ 3883 0,0 *CN* band in the 1942 *g* comet was resolved into individual lines for the first time. Structure, not previously noted, was observed in the λ 4050 bands, recently identified by Herzberg as due to the triatomic molecule CH_2. The main sharp maxima are tentatively considered as the Q branches of the band. A number of the emission features in the visible region were compared with the oxy-ammonia flame and the conclusion reached that they were probably due to the dissociation of NH_3 into NH_2. This suggestion was made quite independently by Swings and Minkowski. No reasonable identification was found for a dozen emission features observed; the occurrence of CH_2 and NH_2 bands in cometary spectra would suggest the possibility that the majority of these unidentified features arise from polyatomic rather than diatomic molecules.

Solar-Type Stars.—Dr. K. O. Wright has continued his studies of solar-type stars. A new curve of growth for the Sun has been derived from Allen's extensive observations of line intensities combined with all available laboratory data, particularly King's *f*-values for *Ti*I and *Fe*I, and Seward's emission intensities for *Mn*I. Solar-line strengths, which have many astrophysical applications, have been determined for many elements from Allen's data and the new curve of growth.

The Victoria observations of line intensities in the spectra of α Canis Minoris, α Persei and λ Cygni have been combined with solar-line strengths to re-derive curves of growth for these stars. Improved values for the turbulent velocities and excitation temperatures of these stellar atmospheres have been determined.

N-type Stars.—The spectra of 20 N-type stars have been photographed by McKellar and Stilwell using a grating spectrograph of high dispersion, 16 A./mm. A weak *Li*I line at λ 6708 was found in nearly all stars, although the equivalent width of the line in all cases was only a few tenths of an angstrom unit compared with eight angstroms for WZ Cass, the star in which the first evidence of lithium outside the Earth and Sun was found. The presence of a moderately weak lithium line would appear to be usual in the N-type spectra.

Radial Velocities.—The observations of the faint Class B stars were continued. An investigation of the motion of the Pleiades cluster was undertaken by Dr. J. A. Pearce.

300 spectra have been secured of 70 cluster members brighter than the 10th magnitude. The radial velocity of the 12 Class B members of the cluster is $+7{\cdot}86 \pm 0{\cdot}38$ km./sec.

The orbits of 12 spectrographic binaries were computed. These included two massive systems, HD 227696 and HD 34333, with total masses of 29 ⊙ and 40 ⊙ respectively. The prediction from the spectrographic data that the former was an eclipsing variable was subsequently confirmed.

A spectrophotometric method was devised by Dr. R. M. Petrie to detect and measure the continuous spectrum of the fainter component of the composite star HD 144208–9. The fainter spectrum was visible through a spectral window created by the wide strong K-line absorption in the primary spectrum.

The spectroscopic magnitude differences in 20 binary systems were determined by R. M. Petrie. The spectral types range from the O-type stars to the solar-type stars, and a good range in relative luminosity is covered.

The ban on the printing of the Observatory researches imposed at the commencement of the war is still in effect.

Royal Observatory, Helwan
(*Director, Dr. M. R. Madwar*)

Time Service.—The time service has been maintained as usual. The error of the standard sidereal clock Shortt No. 1 was determined during 1943 from star transits and during 1944 from transit observations and rhythmic W/T signals; the number of transits amounted to 27 and 14 in 1943 and 1944 respectively.

Rhythmic W/T signals were received daily from Bordeaux and Rugby during 1943 and also during 1944 except for failure of the Bordeaux signals on 100 occasions from the beginning of the year up to August 26, and continuously since that date to the end of the year. Failure to receive the Rugby signals occurred 20 times during 1944.

The standard clock Shortt No. 1 was under repair for 27 days during 1943 January and February, and also from 1944 January 18 to 27 and August 25 to 29; during these periods the Riefler clock was taken as standard. The trouble on the first occasion was traced to a fall of arc; the pendulum was not receiving its proper impulses and soon stopped.

Occultations.—Observations of lunar occultations were continued during 1943; the number of observations amounted to 22, including the occultation of Venus.

The Reynolds reflector was remounted at the beginning of 1943 December but no exposures were made on account of the shortage of plates.

General.—Magnetic, seismological, meteorological and solar radiation observations have been continued as usual.

Bulletin No. 40, on "The Temperature Co-efficients of Helwan Transit Circle", by A. H. Samaha, was issued in 1944 September.

On 1944 September 29 the Observatory was honoured by a visit of H.M. King Farouk. His Majesty has kindly ordered that the Observatory be designated "The Royal Observatory, Helwan".

Union Observatory, Johannesburg
(*Union Astronomer, Dr. W. H. van den Bos*)

Micrometrical measures of double stars with the 26½-inch visual refractor amounted to 183 and 494 during 1943 and 1944 respectively. The number of photographic plates taken with the Franklin-Adams Star Camera of minor planets, comets and variable stars were 368 and 584, while 69 and 47 occultations were obtained, for the two years respectively.

No changes of staff occurred in 1943; Mr. G. Jackson and Mr. E. L. Johnson are on Active Service, and Mr. W. S. Finsen continues to render part-time service to the

Directorate of War Supplies. During 1944 Mr. E. E. Talbot joined the staff as Temporary Mechanical Assistant. Dr. H. van Gent worked at the Observatory throughout 1943 and 1944.

Radcliffe Observatory, Pretoria
(Director, Dr. H. Knox-Shaw, Radcliffe Observer)

Dr. Redman completed the reduction of the spectrograms obtained at the 1940 eclipse. Another search by an improved method for polarization within Fraunhofer lines near the Sun's limb yielded negative results. In an attempt to improve the accuracy of the Fabry method of stellar photometry, Dr. Redman built an experimental apparatus allowing observation by continuous recording. Except on nights with passing cloud, the results showed no improvement over the usual method of discrete exposures, but further trials are needed.

By arrangement with H.M. Astronomer at the Cape, the twin photometric cameras belonging to the Royal Observatory have been attached to the 74-inch mounting, in order to photograph the next Cape Zone ($-35°$ to $-40°$) for photographic and photovisual magnitudes down to 10·5. The Harvard E regions at $-45°$ are being used for comparison. About two-thirds of the necessary plates have already been taken by Dr. Redman and sent to Cape Town for measurement. The question of improving existing magnitudes in the E regions and of reducing them to the international *Pg* and *Pv* systems is being attacked in co-operation with Dr. Stoy. This work, which it is hoped will ultimately remedy the present lack of satisfactory standards in the southern sky, includes fresh intercomparisons of E regions, comparisons with the Pleiades, Hyades and Præsepe, and the checking of magnitude sequences of stars of the same colour, using both the Fabry and other methods.

The Director has continued the observation and reduction of occultations and the construction of a system of homogeneous magnitudes for stars south of $-30°$ based on the Harvard photometric observations. The number of occultations observed during the two years was 105.

The 74-inch mirror and the spectrograph are still unfinished.

Nizamiah Observatory, Hyderabad
(Director, Dr. Akbar Ali)

Routine Work.—Repetition plates in zones $-17°$ to $-23°$ were taken as usual with the astrographic telescope for proper motion work. The revision of the plate-constants in zones $+36°$ to $+39°$ was completed and the MS. of the publication giving the revised values is in the hands of the printers. Similar revision of the plate-constants in zones $-17°$ to $-23°$ is in progress; the positions of the reference stars in this case are obtained from Schlesinger's re-observation of the AG Catalogues—*Transactions of the Yale University Observatory*, Volume XII. The occultations of stars observed at the Nizamiah Observatory in 1943 have been reduced and the results published in *Monthly Notices*. A part of the results of the variable star observations has been communicated to the British Astronomical Association and Harvard College Observatory.

Staff.—Mr. T. P. Bhaskaran, Director, retired in 1944 July after about thirty years of service, and handed over charge to Dr Akbar Ali. Mr. M. K. Bappu, Assistant, retired in 1944 October.

Kodaikanal Observatory, Madras
(Director, Dr. A. L. Narayan)

General.—Despite the absence of many members of the trained staff on war duties, the routine observational and research work have been maintained as usual. A reduction in the daily number of spectroheliograms had to be effected on account of shortage of photographic plates.

Solar Physics.—In 1944 there has been a further decline in all forms of solar activity.

Photoheliograms were obtained on 290 days: calcium flocculi plates on 285 days: calcium prominence plates on 265 days and *Hα* flocculi plates on 251 days. One calcium flocculus plate for each day was reserved for transmission, as in former years, to the Solar Physics Observatory, Cambridge, after the cessation of hostilities.

Daily character figures of solar activity according to *Hα* bright flocculi, *Hα* dark markings and calcium flocculi were communicated to the Royal Observatory, Greenwich, for transmission to Professor Brunner of Zürich.

Observations with the Hale spectrohelioscope were made on all days except on Sundays and holidays whenever weather permitted. A list of bright eruptions together with the times of observations made at the spectrohelioscope were also communicated to Greenwich for transmission to Zürich.

A high-latitude spot (45° N.) and its attendant faculæ, indicating the beginning of a new cycle of solar activity, were recorded on 1944 August 14. The spot existed only for one day, but the faculæ could be observed continuously for three days.

Research Work.—The work on the intensities and contours of Fraunhofer lines has been continued.

From a study of the *CN* band at λ 3883 with the high-dispersion Littrow spectrograph of this observatory, K. N. Rao has derived temperatures of 5000° and 4500° K at the centre and limb of the Sun respectively.

Taking advantage of the minimum period of solar activitity, high-dispersion spectrograms of the Sun's chromosphere, outside the eclipse, were obtained in *Hβ* and *Hγ* for the spectrophotometry of the chromosphere.

Commonwealth Solar Observatory, Canberra, Australia
(*Director, Dr. R. v. d. R. Woolley*)

Solar and Magnetic Work.—Daily sunspot sketches and visual observations with the spectrohelioscope were recommenced at the end of 1942. A study has been made of the relation between M regions and the observable solar features, viz. sunspots, flocculi, coronal streamers, etc., and the conclusions published in the *Monthly Notices.* Further numerical studies relating to the latitude of M regions have not yielded any significant results.

Earth-current recordings have been made since 1942 October, and provisional geomagnetic K-indices deduced from them for the purpose of making a day-to-day investigation of the relation between solar phenomena and magnetic disturbances. Corresponding disturbances in the ionosphere have also been investigated.

Time Service.—Preparations for transferring the Commonwealth time service from Melbourne to Canberra are well advanced. The transit telescope hut is almost complete, and the telescope itself is being fitted with an impersonal micrometer, reversing gear and other accessories in the observatory workshop. Observations are limited at present to comparisons of the observatory Shortt with the quartz clock at the General Post Office, Melbourne, and with local and overseas radio time-signals.

Melbourne Observatory
(*Officer-in-Charge, Dr. J. M. Baldwin*)

The Melbourne Observatory passed under the control of the Commonwealth Solar Observatory on 1944 March 8.

During the years 1943–44 the time service was continued and progress made in the preparation of material of the Melbourne zone of the *Astrographic Catalogue* for publication.

Riverview College Observatory, Riverview, N.S.W.
(Director, Rev. D. O'Connell, S.J.)

Photographic work on variable stars has been carried on, though research has necessarily been limited by shortage of staff and other difficulties due to the war.

A number of comet plates were measured by the Director during a visit to Mount Stromlo Observatory. The results were published in the *Monthly Notices*.

Twenty-three occultations were observed in the first ten months of 1944 and sent to the Nautical Almanac Office.

Magnitudes were determined for comparison stars for Nova Puppis (1942) (*Bulletin* 245, N.S.W. Branch, B.A.A.)

Professor F. J. M. Stratton visited the observatory in 1943 August.

Sydney Observatory
(Government Astronomer, Mr. H. W. Wood, M.Sc.)

The programme of work on the *Astrographic Catalogue* has been continued during the period under review, volumes 17 and 19 have been printed, further transit observations for reference stars made and a good number of plate constants computed.

The occultations predicted in the *Nautical Almanac* have been observed when possible and the reduction carried on in co-operation with the Nautical Almanac Office. The programme of observations of double stars has proceeded when opportunity occurred. A series of observations of Nova Puppis was published in the *Journal of the Royal Society of New South Wales*.

The civil work, consisting of the supply of astronomical information for legal purposes, the time service, and answering general inquiries has been carried on. The educational work of the Observatory was continued, and lectures and demonstrations on astronomy delivered regularly.

Dominion Observatory, Wellington, New Zealand
(Acting Director, Mr. R. C. Hayes)

Time Service.—In addition to the normal time service, extensions have been necessary to meet the needs of the Armed Forces in New Zealand and the Pacific War Zone.

During 1943 a new design of synchronizer was fitted to the signal clocks with a view to reducing the effects of earthquakes on them.

Astronomy.—At present, a large amount of astronomical work normally carried out by the Carter Observatory has to be undertaken by the Dominion Observatory. This includes daily sunspot observations, by projection, using the 5-inch refractor of the Royal Society of New Zealand.

In 1943 September Professor F. J. M. Stratton visited the Observatory.

Staff.—Two members of the staff are absent on service connected with the war, one of them is overseas.

Mr. Robert Barker's Observatory, Cheshunt, Hertfordshire

The 1943–44 opposition of Mars was well observed and detailed drawings were obtained over most longitudes. The light-coloured areas traversed by S. latitude 40° N. of Mare Chronium were definitely distinct, and regions Eridania, Ausonia, Hellas, Noachis, Argyre, Phæthontis and Electris were recorded with their dividing canals. Close confirmation was obtained from correspondents in the United States, and from B. Burrell (Doncaster). Some of these regions and canals have not often been recorded in England. From S. latitude 40° to N. latitude 40° over 50 canals were obtained.

Saturn's open Ring system has afforded glimpses of hazy, ill-defined divisions, or

streaks, in (or on) Rings A and B, in marked contrast to Cassini's Division. Here I confirmed my American co-workers.

The lunar cleft systems of Ariadæus, Hyginus, Triesnecker, Gassendi (interior), Hesiodus, Sirsalis and W. of Mersenius received close investigations and yielded some curious results, especially the last-named system. Mars' opposition was not favoured with many really good nights, although a marked lessening of enemy night activity made observations more comfortable.

Telescope: clock-driven 12·6-inch Calver, 120-inch focal length.

Mr. J. Evershed's Observatory, Ewhurst, Surrey

The liquid prism spectrograph has been employed in photographing spot spectra both in 1943 and 1944, with the object of studying the different magnetic effects in the umbræ and penumbræ of spots, especially in those regions where the magnetic effect gives lines classed as doublets in the umbræ.

An intensive study of the shifts of the sodium lines at the centre of the Sun's disk and at the limb is being carried out, and a large number of high-dispersion spectra of Sun and vacuum tube have been obtained and measured. The precision which results from the positive on negative method of measuring has revealed certain small changes of wave-length of the solar lines, or changes in the general shift of the lines towards red, which at times considerably exceeds the relativity effect, as has been found previously for the iron lines.

Dr. J. L. Haughton's Observatory, Teddington

Thirteen occultations were observed in 1943 and the first half of 1944. In July of the latter year, however, it was considered advisable to remove the larger optical parts of the telescope to a place of greater safety. In the spring of 1944 some drawings of Jupiter were made in order to obtain practice with a view to taking up the study of the planet after the war. Various improvements have been made in the equipment of the observatory.

Mr. M. B. B. Heath's Observatory, Kingsteignton, Devon

Daylight observations of Mercury were made on 27 days in 1943 and 5 drawings made. In 1944 observations were made on 15 days. Daylight observations of Venus were made on 49 days in 1943 and 11 drawings made. Between 1943 April 18 and 1944 April 15 Mars was observed on 73 days and 31 drawings made. Approximate positions of Comet Whipple were obtained on 8 nights and of Comet van Gent on 4 nights.

All results and copies of drawings were sent to the British Astronomical Association.

Mr. F. M. Holborn's Observatory, Streatham

In 1943 on 162 nights 1007 observations were made of variable stars and novæ together with a few drawings of Mars.

In 1944 on 132 nights 1010 observations were made of variable stars and novæ. Records were sent to the British Astronomical Association.

Mr. A. M. Newbegin's Observatory, Worthing, Sussex

The usual routine solar observations were made and the results are given for two years:

Mean Daily Frequency	1943	1944
Prominences . .	5·22	4·79
Sunspots . . .	1·25	1·09

Observations for solar flares were continued and the results forwarded to Mr. H. W. Newton at Greenwich for inclusion in the *Bulletin* published under the auspices of the International Astronomical Union.

According to the Worthing records, the minimum of the last cycle occurred in 1944 May, and the new cycle was ushered in by a very active area of bright hydrogen in high southern latitude in the middle of June. As is usual at this Observatory, the complete results for each solar rotation have been sent to the Director of the Solar Section of the British Astronomical Association for incorporation in his quarterly summaries of solar activity.

Observations in 1944 were vitiated by reason of the fact that they did not begin until April owing to domestic rearrangements, and from August to the end of the year the weather was exceptionally bad.

Mr. B. M. Peek's Observatory, Solihull, Birmingham

Visual observations of the major planets were continued during 1943 and 1944, the systematic study of the surface features of Jupiter having precedence over everything.

A remarkably fine spell of observing conditions that occurred during the early months of 1943, while a great disturbance in Jupiter's southern hemisphere was in progress, was largely responsible for the recording of 3093 estimates of the transit times of spots across the planet's central meridian during the apparition of 1942–43. In addition, many detailed drawings were made and the Society's Cooke filar micrometer was employed in obtaining a series of measurements of the latitudes of the belts.

Seven occultations of stars by the Moon were recorded in 1943.

Conditions during 1944 were less favourable, the 1943–44 apparition of Jupiter providing 1369 transit observations besides drawings and micrometer measurements.

Eight lunar occultations were observed during the year.

Considerable time has been given to the reduction and co-ordination of the work of members of the Jupiter Section of the British Astronomical Association. The Thirty-first Report of the section, dealing with the apparitions of 1937, 1938 and 1939–40, was published by the Association in 1943, and the Thirty-second Report, covering 1940–41 and 1941–42, in 1944.

REPORTS ON THE PROGRESS OF ASTRONOMY

STELLAR DYNAMICS

Since the early investigations of Eddington, Jeans and Schwarzschild, two problems have occupied a central position in stellar dynamics. The first of these relates to stellar encounters, its importance for stellar dynamics and the manner in which it is best incorporated into the framework of a general theory. The second relates to the consequences for the dynamical theory which the known kinematics of stellar motions implies. Through recent investigations, the solutions to these two problems have reached a comparatively advanced stage and it would seem proper to review in general terms the results to which they have led.

I. Stellar Encounters

Considering first the problem relating to stellar encounters, it is simplest to picture them in terms of the simple two-body problem. On this idealization, during an encounter, each star describes a hyperbola relative to the other, and the result of an encounter is that each star suffers certain increments, $\Delta u_{\parallel}$ and $\Delta u_{\perp}$, in the velocity in directions which are parallel and perpendicular respectively to the initial direction of motion. While the exact amounts of these increments $\Delta u_{\parallel}$ and $\Delta_{\perp}$ which a star experiences will differ in individual cases, it is evident, in view of the long-range character of the inverse square force, that for the encounters occurring most frequently, these will be extremely small compared to the initial velocities of the stars. The directions and magnitudes of the motions of stars can accordingly be influenced by stellar encounters only as the result of the cumulative effect of a large number of encounters. It is, therefore, seen that in this respect the inverse square encounters which are relevant in stellar dynamics, differ in a fundamental way from those with which we are familiar in gas kinetic theory. For, in ordinary gas theory, single encounters in general lead to radical changes in the directions and magnitudes of the motions of individual molecules. Indeed the analogy which has sometimes been made between gas dynamics and stellar dynamics does not seem very appropriate: it would appear far closer to draw a comparison between the motions of stars as influenced by stellar encounters and Brownian motion. For, as is well known, colloidal particles describing Brownian movement owe their motions to collisions with the molecules of the surrounding fluid though individual collisions can hardly make "an impression" on the particle: again it is the cumulative effect of a large number of collisions that is responsible for the observed motions. This analogy which exists between Brownian motion and the motions induced by stellar encounters is far-reaching and is capable of a wide generalization. We shall accordingly pursue this a little further.

In describing Brownian motion we distinguish between random fluctuations and the systematic decelerations consequent to the operation of Stokes's law. This distinction, which is generally made, is brought out most clearly in Langevin's form for the equation of motion

$$\frac{d\mathbf{u}}{dt} = -\eta\mathbf{u} + \mathbf{A}(t) \qquad (1)$$

of a Brownian particle where $\mathbf{u}$ denotes the velocity of the particle. According to this equation, the influence of the surrounding medium can be split up into two parts: first, a systematic part $-\eta\mathbf{u}$ representing a *dynamical friction* experienced by the particle, and, second, a fluctuating part described by $\mathbf{A}(t)$. In the classical theories of Brownian

motion the frictional term $-\eta\mathbf{u}$ is assumed to be governed by Stokes's law, while the fluctuating part $\mathbf{A}(t)$ is assumed to vary extremely rapidly compared with the variations of $\mathbf{u}$, and in such a way that the increment in velocity experienced by the particle due to this term and during two successive intervals $(t,\ t+\Delta t)$ and $(t+\Delta t,\ t+2\Delta t)$ are not correlated if Δt is large compared with the average time between successive collisions. The manner in which the two terms in equation (1) operate is understood most clearly if we consider the increment in the velocity $\Delta\mathbf{u}$ which the particle experiences in an interval Δt satisfying the conditions stated. Writing

$$\Delta\mathbf{u} = -\eta\mathbf{u}\Delta t + \delta\mathbf{u}(\Delta t) \tag{2}$$

the term $\delta\mathbf{u}(\Delta t)$ is of the nature of an "error" with a Gaussian distribution. Moreover,

$$\overline{\delta\mathbf{u}} = 0; \qquad \overline{|\delta\mathbf{u}|^2} = 2q\Delta t, \tag{3}$$

where q may be called the *diffusion coefficient* in the velocity space. In order that particles describing Brownian motion in accordance with the foregoing laws restore and maintain a Maxwellian distribution of velocities among themselves, it is necessary that q and η are related according to

$$q = \tfrac{1}{3}\,\overline{|\mathbf{u}|^2}\,\eta, \tag{4}$$

where $\overline{|\mathbf{u}|^2}\,(=3kT/m)$ denotes the mean square velocity of the particles. And finally, it can be shown that the function $W(\mathbf{u}, t)$ governing the probability of occurrence of the velocity $\mathbf{u}$ at time t for a Brownian particle must satisfy the Fokker-Planck equation

$$\frac{\partial W}{\partial t} = \mathrm{div}_{\mathbf{u}}\,(q\,\mathrm{grad}_{\mathbf{u}} W + \eta W\mathbf{u}). \tag{5}$$

According to this equation we may visualize the motions of the representative points in the velocity space as a *process of diffusion* in which the rate of flow across an element of surface $d\sigma$ is given by

$$-(q\,\mathrm{grad}_{\mathbf{u}} W + \eta W\mathbf{u})\,.\,\mathbf{1}_{d\sigma}\,d\sigma, \tag{6}$$

where $\mathbf{1}_{d\sigma}$ is a unit vector normal to the element of surface considered.

Returning to the stellar case, we shall now show how the effect of stellar encounters can be treated in a manner exactly analogous to the theory of Brownian motion described above.

A straightforward analysis based on the classical two-body problem leads to the following expressions for the increments in velocity $\Delta u_{\parallel}$ and $\Delta u_{\perp}$ which a star of mass m and velocity $\mathbf{u}$ suffers as the result of an encounter with another star of mass m_1 and velocity $\mathbf{v}_1$:

$$\Delta u_{\parallel} = -\frac{2m_1}{m_1+m}[(u - v_1\cos\theta)\cos\psi + v_1\sin\theta\cos\Theta\sin\psi]\cos\psi \tag{7}$$

and

$$\Delta u_{\perp} = \pm\frac{2m_1}{m_1+m}[u^2 + v_1{}^2 - 2uv_1\cos\theta - \{(u - v_1\cos\theta)\cos\psi + v_1\sin\theta\cos\Theta\sin\psi\}^2]^{1/2}\cos\psi. \tag{8}$$

In equations (7) and (8) θ denotes the angle between the two vectors $\mathbf{u}$ and $\mathbf{v}_1$, Θ the inclination of the orbital plane to the plane containing $\mathbf{u}$ and $\mathbf{v}_1$,

$$\cos\psi = \{1 + D^2(u^2 + v_1{}^2 - 2uv_1\cos\theta)^2/G^2(m_1+m)^2\}^{-1/2}, \tag{9}$$

D the impact parameter and G the constant of gravitation.

Now consider an interval of time Δt long compared with the time required for two average stars to separate by a distance equal to the average distance between the stars but short compared with the intervals during which the velocity of a star may be expected

to change appreciably. (In practice this implies that $\Delta t \sim 10^6$ years.) During such an interval of time the increments in velocities $\Sigma\Delta u_{\|}$ and $\Sigma\Delta u_{\perp}$ which a star with an initial velocity $\mathbf{u}$ may be expected to suffer in directions parallel and perpendicular respectively to its initial direction of motion, can be obtained by simply averaging the expressions for $\Delta u_{\|}$ and $\Delta u_{\perp}$ over the relevant ranges of the various parameters describing an encounter. With certain approximations appropriate for the problem it is found that

$$\Sigma\Delta u_{\|} = -4\pi m_1(m_1+m)NG^2\frac{1}{|\mathbf{u}|^2}\left(\log\left[\frac{D_0\overline{|\mathbf{u}|^2}}{G(m_1+m)}\right]\right)\Delta t\int_0^{|\mathbf{u}|} f(v_1)dv_1 \tag{10}$$

and

$$\Sigma\Delta u_{\perp} = 0, \tag{11}$$

where D_0 denotes the average distance between the stars, N the number of stars per unit volume, $\overline{|\mathbf{u}|^2}$ the mean square velocities of the "field stars", and $f(v_1)$ the distribution function governing the probability of occurrence of a star with velocity $|\mathbf{v}_1| = v_1$. According to equation (10), we may say that the star experiences dynamical friction with a coefficient of dynamical friction η given by

$$\eta = 4\pi N m_1(m_1+m)\frac{G^2}{|\mathbf{u}|^3}\left(\log\left[\frac{D_0\overline{|\mathbf{u}|^2}}{G(m_1+m)}\right]\right)\int_0^{|\mathbf{u}|} f(v_1)dv_1. \tag{12}$$

It may be noted that in contrast to the classical case, η is now a function of $|\mathbf{u}|$ such that

$$\eta \to \eta_0 = \text{constant} \quad \text{as} \quad |\mathbf{u}| \to 0, \tag{13}$$

while

$$\eta \to \text{constant}\,|\mathbf{u}|^{-3} \quad \text{as} \quad |\mathbf{u}| \to \infty. \tag{14}$$

This decrease in the frictional coefficient as $|\mathbf{u}|$ increases is of course to be expected on physical grounds.

Again, from equation (7) we similarly find after averaging over the various quantities that

$$\Sigma\Delta u_{\|}^2 = \frac{8}{3}\pi N m_1^2\frac{G^2}{|\mathbf{u}|^3}\left(\log\left[\frac{D_0\overline{|\mathbf{u}|^2}}{G(m_1+m)}\right]\right)\overline{|\mathbf{u}|^2}\,\Delta t\int_0^{|\mathbf{u}|} f(v_1)dv_1, \tag{15}$$

which represents, in analogy, with equation (3) a diffusion in the velocity space. The completeness of the analogy of our present problem with Brownian motion is seen even more clearly when we note that, according to equations (12) and (15) (*cf.* eq. (4)),

$$\frac{\Sigma\Delta u_{\|}^2}{\eta\Delta t} = \frac{2}{3}\frac{m_1}{m+m_1}\overline{|\mathbf{u}|^2}. \tag{16}$$

It would therefore appear that the most convenient way in which we may study the influence of stellar encounters is to picture it as causing a Brownian motion. Quantitatively the changes in velocities which a star experiences on this account will be governed by the Fokker-Planck equation (5) with η, now given by equation (12). When there is an external field of force ($\mathbf{K}$) present, the phenomenon in the six-dimensional phase space of a single star will similarly be governed by the equation

$$\frac{\partial W}{\partial t} + \mathbf{u}\,.\,\text{grad}_{\mathbf{r}}\,W + \mathbf{K}\,.\,\text{grad}_{\mathbf{u}}\,W = \text{div}_{\mathbf{u}}\,(q\,\text{grad}_{\mathbf{u}}\,W + \eta W\mathbf{u}). \tag{17}$$

We shall now illustrate the usefulness of incorporating stellar encounters in a general dynamical theory in the manner we have described, by considering the problem of the rate of escape of stars from galactic clusters like the Pleiades.

As was first clearly recognized by Ambarzumian and Spitzer, an important factor in the evolution of the galactic and the globular clusters is their gradual impoverishment

due to the escape of stars. We shall now show how we can evaluate this rate of escape of stars quite rigorously.

To be specific, we shall suppose that in order that a star may escape from a cluster it is only necessary that it acquire a velocity greater than or equal to a certain critical velocity which we shall denote by v_∞. On this assumption the probability that a star will have acquired the necessary velocity of escape during a certain time t can be evaluated quite simply from the probability $p(v_0, t)dt$ that a star having an initial velocity $|\mathbf{u}| = v_0$ at time $t = 0$ will acquire for the *first time* the velocity $|\mathbf{u}| = v_\infty$ during t and $t + dt$. For, on integrating $p(v_0, t)$ over t from 0 to t, we shall obtain the probability $Q(v_0, t)$ that the star will have acquired the velocity v_∞ during the entire interval from 0 to t. And finally, averaging $Q(v_0, t)$ over the relevant range of the initial velocities, we shall obtain the expectation $Q(t)$ that a star will have acquired the velocity v_∞ during the time t.

The advantage of formulating the problem in the manner described above is that the function $p(v_0, t)$ can be determined in terms of the solution of equation (5) which satisfies certain appropriate boundary conditions. For, remembering the interpretation of this equation as representing a process of diffusion taking place in the velocity space, it is evident that $p(v_0, t)$ will be given by

$$p(v_0, t) = -\left[4\pi q\,|\mathbf{u}|^2 \frac{\partial W(|\mathbf{u}|, t)}{\partial |\mathbf{u}|}\right]_{|\mathbf{u}| = v_\infty}, \tag{18}$$

where $W(|\mathbf{u}|, t)$ denotes a spherically symmetric solution of equation (5) (with η given by equation (12)), which satisfies the boundary conditions

$$W(|\mathbf{u}|, t) = 0 \quad \text{for} \quad |\mathbf{u}| = v_\infty \qquad \text{for all } t > 0 \tag{19}$$

and

$$W(|\mathbf{u}|, t) \to \frac{1}{4\pi {v_0}^2}\delta(|\mathbf{u}| - v_0) \qquad \text{as } t \to 0, \tag{20}$$

where δ stands for the δ-function of Dirac. Passing over the method by which the foregoing boundary value problem has been solved, we may quote the final result. It is found that to a sufficient approximation we can write

$$Q(t) = 1 - e^{-0.0075t/t_0}, \tag{21}$$

where

$$\frac{1}{t_0} = \lim_{|\mathbf{u}| \to 0} \eta = 8\pi N m^2 G^2 \left(\log\left[\frac{D_0 \overline{|\mathbf{u}|^2}}{2Gm}\right]\right)\left(\frac{3}{2\,\overline{|\mathbf{u}|^2}}\right)^{3/2} \frac{4}{3\pi^{1/2}}. \tag{22}$$

According to this definition of t_0, it is of the order of the reciprocal of the coefficient of dynamical friction for values of velocities of the order of the root mean square velocity in the system. We may therefore take t_0 as a measure of the time required to restore a Maxwellian distribution starting from an arbitrary initial distribution of velocities. In other words, t_0 is a measure of the *time of relaxation* of the system.

Returning to equation (21), we conclude that the mean life of a cluster may be estimated to be $133t_0$. For the Pleiades, $\sqrt{\overline{|\mathbf{u}|^2}}$ is estimated at 0·43 km./sec. Using this value of $\sqrt{\overline{|\mathbf{u}|^2}}$ and the known dimensions and population of this cluster, the time of relaxation t_0 is found to be 2×10^7 years. Its mean life is therefore 3×10^9 years. This estimate for the mean life of the Pleiades is typical of galactic clusters, and we can accordingly find in these estimates an argument in favour of the currently adopted time scale of the order of 3×10^9 years.

We have discussed this treatment of the escape of stars from clusters at this length only to illustrate the advantage of formulating the effect of stellar encounters on the motions of stars in the manner of the theory of Brownian motion and using the generalized Fokker-Planck equation (17) as the fundamental equation of stellar dynamics.

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II. Dynamics of Stellar Systems with Differential Motions and Star Streaming

Turning our attention next to the second of the two major problems stated at the outset, it is first necessary to formulate the laws of stellar kinematics in a sufficiently general way. It may be said that the two principal characteristics of stellar motions in a system like our galaxy are (1) the existence of a *field of differential motions* and (2) the phenomenon of *star streaming* which the distribution of the peculiar velocities exhibit. We owe to Milne the first clear formulation of the first of these two concepts: essentially it implies that we are able to define in an unambiguous way a local standard of rest for each small region of the galaxy and that the different local standards of rest are in relative motion. In other words, we are able to express the function $\Psi(x, y, z;\ U, V, W;\ t)$ governing the distribution of the velocities (U, V, W) in the various parts of the galaxy (x, y, z) in the form

$$\Psi = \Psi(x, y, z;\ U - U_0, V - V_0, W - W_0;\ t), \tag{23}$$

where U_0, V_0 and W_0 (defining the field of differential motions) are functions of position and time only. (Sometimes, as when dealing with the system of the high velocity stars, it may be necessary to generalize the foregoing and write

$$\Psi = \Sigma_i \Psi_i(x, y, z;\ U - U_0^{(i)}, V - V_0^{(i)}, W - W_0^{(i)};\ t), \tag{24}$$

where the summation over the index i corresponds to the fact that under these circumstances we are to regard the stellar system as (formally) consisting of several distinct sub-systems.) On the other hand the existence of star streaming implies that the distribution of the peculiar velocities $(u = U - U_0;\ v = V - V_0;\ w = W - W_0)$ is governed by Schwarzschild's ellipsoidal law:

$$\Psi(u, v, w) = \frac{N}{\pi^{3/2}} \begin{vmatrix} a & h & g \\ h & b & f \\ g & f & c \end{vmatrix}^{1/2} e^{-(au^2 + bv^2 + cw^2 + 2fvw + 2gwu + 2huv)}, \tag{25}$$

where the *coefficients of the velocity ellipsoid* a, b, c, f, g and h, and the number of stars per unit volume, N, at (x, y, z), may all be expected to be functions of position and time. Combining equations (23) and (25) we have

$$\Psi = e^{-(\mathbf{Q} + \sigma)}, \tag{26}$$

where $\mathbf{Q}$ is a general homogeneous quadratic form in the residual velocities and

$$e^{-\sigma} = \frac{N}{\pi^{3/2}} \begin{vmatrix} a & h & g \\ h & b & f \\ g & f & c \end{vmatrix}^{1/2} \tag{27}$$

With the statement of stellar kinematics expressed in a distribution function of the form (26), our problem now is, what does this imply for dynamics? To answer this question we have simply to examine the conditions under which the equation of continuity (eq. (17)) will admit a solution of the form (26), or more generally a solution of the form

$$\Psi = \Psi(\mathbf{Q} + \sigma), \tag{28}$$

where Ψ is an arbitrary function of the argument specified. One circumstance simplifies this problem considerably. And that is, under the present conditions in the galaxy we may ignore the collision terms in this equation. The reason why we can do this is the following: as we have seen in the preceding section, the relative importance of the effect of stellar encounters in influencing the motions of stars can be inferred from a knowledge of the time of *relaxation* t_0. For, if we are primarily interested in time-intervals which are short compared to t_0, it is evident that the influence of stellar encounters can be ignored. And it is readily verified that under the conditions, for example in the general neighbourhood of the Sun, $t_0 \sim 10^{14}$ years, and the time-intervals we are interested in are far shorter than this. Accordingly, we may reformulate our fundamental problem in the following terms:—

Under what conditions will the equation of continuity

$$\frac{D\Psi}{Dt} = \frac{\partial \Psi}{\partial t} + U\frac{\partial \Psi}{\partial x} + V\frac{\partial \Psi}{\partial y} + W\frac{\partial \Psi}{\partial z} - \frac{\partial \mathbf{V}}{\partial x}\frac{\partial \Psi}{\partial U} - \frac{\partial \mathbf{V}}{\partial y}\frac{\partial \Psi}{\partial V} - \frac{\partial \mathbf{V}}{\partial z}\frac{\partial \Psi}{\partial W} = 0, \tag{29}$$

regarded as a partial differential for Ψ, *admit a solution of the form* (28)? (In equation (29) we have used $\mathbf{V} = \mathbf{V}(x, y, z; t)$ to denote the gravitational potential.)

For the assumed form of Ψ the equation of continuity reduces to

$$\frac{D}{Dt}(\mathbf{Q} + \sigma) = 0. \tag{30}$$

In this form we recognize that our problem is essentially one of determining the field of force in which a particle describing an orbit may possess an integral which is a general quadratic form in the velocities. Up to a point the progress toward the solution of this problem is simple and straightforward. We substitute for $\mathbf{Q} + \sigma$ in equation (30) and find that it breaks up into a system of twenty partial differential equations. Of these, a first group of ten equations involves only the coefficients of the velocity ellipsoid, while a second group of six equations involves the differential motions as well. These sixteen equations can be solved explicitly and suffice to determine the space dependence of the coefficients of the velocity ellipsoid and the components of the differential motion. However, their dependence on time is left unspecified, as the general solutions introduce a large number of arbitrary functions of time. (Actually, the general solution of these equations introduces twenty arbitrary functions of time and six constants of integration.) But it should not be assumed that the solution to the physical problem involves this degree of arbitrariness. Severe restrictions are imposed by the last four equations, which for their validity require the satisfaction of certain integrability conditions. These integrability conditions appear as a set of six simultaneous partial differential equations for $\mathbf{V}(x, y, z; t)$, and the problem reduces to discussing the compatibility of these equations. In its most general form this discussion has not so far been completed. But a number of special solutions have been found, and we shall briefly indicate the nature of some of the more important of these.

Considering as our first example stellar systems in steady states, it is found that three of the six integrability conditions which we mentioned reduce to a single linear homogeneous partial differential equation for $\mathbf{V}(x, y, z)$. This equation for $\mathbf{V}$ can be

solved quite generally, and shows that with a suitable choice of the origin and orientation of our co-ordinate axes, $\mathbf{V}$ must have the form

$$\mathbf{V}(x, y, z) \equiv \mathbf{V}(\varpi;\ z + \alpha\vartheta), \tag{31}$$

where ϖ denotes the distance from the Z-axis, ϑ the azimuthal angle measured in the (x, y)-plane and α a constant. In other words, $\mathbf{V}$ must in general be characterized by *helical symmetry*. However, for finite stellar systems it is evident that we must require that $\alpha = 0$; for, the single valuedness of $\mathbf{V}$ will otherwise require that $\mathbf{V}$ is periodic in z with a period $2\pi\alpha$. We have accordingly the following fundamental theorem:—

For stellar systems with differential motions which are in steady states and are of finite spatial extent the gravitational potential $\mathbf{V}$ *must necessarily be characterized by axial symmetry.*

The remaining integrability conditions may now be discussed, and it appears that for gravitational potentials which have an axial symmetry but are otherwise unrestricted, the most general integral which is quadratic in the velocities must be a combination of the energy and the angular momentum integrals:

$$I_1 = \Pi^2 + \Theta^2 + Z^2 + 2\mathbf{V}; \qquad I_2 = \varpi\Theta, \tag{32}$$

where Π, Θ and Z are the linear velocities in the radial, transverse and the Z-directions respectively. Thus $\mathbf{Q} + \sigma$ must be reducible to the form:

$$\mathbf{Q} + \sigma = \alpha I_1 + \beta I_2^2 + \gamma I_2, \tag{33}$$

where α, β and γ are constants. Solutions of this general form have been used particularly by Oort and Lindblad.

A second example we shall consider relates to the two-dimensional problem treating stellar systems with circular symmetry and in non-steady states. It can be shown that in this case the most general non-trivial form of $\mathbf{V}(\varpi, t)$ which is compatible with the integrability conditions of the problem is

$$\mathbf{V}(\varpi, t) \equiv -\frac{\dot{\phi}}{2\phi}\varpi^2 + \frac{1}{\phi^2}\mathbf{V}_1\left(\frac{\varpi}{\phi}\right), \tag{34}$$

where $\mathbf{V}_1$ is an arbitrary function of the argument specified and ϕ is a certain function of time only which appears in the solutions for the coefficients of the velocity ellipse and the components of the differential motions. Thus:

$$a = \phi^2 + \kappa_2 y^2; \qquad b = \phi^2 + \kappa_2 x^2; \qquad h = -\kappa_2 xy \tag{35}$$

and

$$U_0 = \frac{\dot{\phi}}{\phi}x + \frac{\beta y}{\phi^2 + \kappa_2\varpi^2}; \qquad V_0 = \frac{\dot{\phi}}{\phi}y - \frac{\beta x}{\phi^2 + \kappa_2\varpi^2}, \tag{36}$$

where κ_2 and β are constants. Moreover,

$$\sigma = -\frac{\beta^2\varpi^2}{\phi^2 + \kappa_2\varpi^2} + 2\mathbf{V}_1\left(\frac{\varpi}{\phi}\right) + \text{constant}. \tag{37}$$

With the solutions for a, b, h, U_0 and V_0 given by equations (35) and (36), we find that the velocity ellipse can be reduced to the form

$$\mathbf{Q} = \phi^2(\Pi - \Pi_0)^2 + (\phi^2 + \kappa_2\varpi^2)(\Theta - \Theta_0)^2, \tag{38}$$

where

$$\Pi_0 = \frac{\dot{\phi}}{\phi}\varpi \quad \text{and} \quad \Theta_0 = -\frac{\beta\varpi}{\phi^2 + \kappa_2\varpi^2}. \tag{39}$$

While the conditions of the problem thus far introduced do not restrict ϕ and allow it to be an arbitrary function of time, it would appear that other considerations will in fact

limit ϕ to a particular form. Thus, if we should suppose that the form of the solution (34) is valid also for $\varpi \to \infty$, it is evident that the boundedness of $\mathbf{V}$ will demand that

$$-\frac{\ddot{\phi}}{2\phi} = \text{constant}\,\frac{1}{\phi^4}. \tag{40}$$

For the term $-(\ddot{\phi}/2\phi)\varpi^2$ must be cancelled by a term in ϖ^2 in $\mathbf{V}_1$, and this can occur only with a coefficient proportional to ϕ^{-4} (*cf.* eq. (34)). Equation (40) is readily integrated and leads for ϕ to a solution of the form

$$\phi = \phi_0[1 + \alpha(t - t_0)^2]^{1/2}, \tag{41}$$

where ϕ_0, α and t_0 are constants.

The third and final example we shall refer to and for which the general solution has been found relates to stellar systems in non-steady states and with a spherical distribution of the residual velocities. For this case the distribution function has the form

$$\Psi' \equiv \Psi'\{a[(U - U_0)^2 + (V - V_0)^2 + (W - W_0)^2] + \sigma\}, \tag{42}$$

where Ψ' is an arbitrary function of the argument specified and a, U_0, V_0, W_0 and σ are all functions of position and time, arbitrary in the first instance. It can be shown that this form of Ψ' implies that $\mathbf{V}$ satisfies a certain linear non-homogeneous partial differential equation in x, y, z and t. This equation for $\mathbf{V}$ has been solved, and while its discussion is too long to undertake within the limits of this report, it may be stated that the importance of this solution for general dynamical theory is that there is reason to believe that the form for $\mathbf{V}$ which is thus disclosed is likely to be in fact the most general form which is compatible with our fundamental kinematical postulates. We may further add that the solution for $\mathbf{V}$ and particularly σ are of sufficient generality as to be suggestive for the interpretation of spiral structure in extra-galactic nebulæ.

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In the two preceding sections we have summarized the present state of the two classical problems of the subject. We shall now consider some other problems of more recent origin.

III. The Statistics of the Gravitational Field arising from a Random Distribution of Stars

In section I we idealized stellar encounters in terms of the two-body problem of classical dynamics. This idealization, while it is the simplest and the most convenient one to make, has its shortcomings. For example, in evaluating quantities like $\Sigma\Delta u_{\|}$ and $\Sigma\Delta u_{\|}^2$ we find that the integrals over the impact parameter D diverge logarithmically if they are extended from 0 to ∞. In practice this divergence is avoided by limiting the range of integration from 0 to a certain maximum value D_0 which is assumed to be of the order of the average distance between the stars. This procedure is justified on the grounds that for values of the impact parameter which are of the order of, or greater than, the average distance between the stars, the two-body approximation must fail and the concept of individual two-body encounters must be replaced by that of a multiple encounter in which several stars partake. This argument is, of course, sound,

but it would be preferable if the arbitrariness in the cut-off value of D could be avoided and a general theory developed in which the influence of all the neighbouring stars on a given one will be taken into account. It would appear that the elements for such a theory of multiple encounters will be provided by an analysis of the fluctuating gravitational field to which a star is subjected on account of the changing complexion of the local stellar distribution. While a rigorous analysis of such fluctuating fields is likely to be very difficult, a model for analysis which suggests itself and which would seem appropriate for the conditions under which the two-body approximation fails, is the following:—

Let the fluctuations in the stellar distribution which occur be subject only to the restriction of a constant average number of stars per unit volume. Further, let the stars be assumed to describe linear trajectories independently of each other and with a Gaussian distribution of the velocities in a suitably chosen frame of reference. We ask: What is the statistics of the fluctuating gravitational field in such a system? Or, more specifically: What is the probability distribution of the force per unit mass, $\mathbf{F}$, acting on a star? What is the rate of change to be expected in $\mathbf{F}$ acting on a star moving with a velocity $\mathbf{v}$? What is the correlation in the forces acting on a star at two different instants of time? And finally, what is the correlation in the forces acting simultaneously at two points in the system separated by a finite distance? We shall now briefly indicate how these questions have been answered.

The force per unit mass acting on a star at a particular instant of time (say $t=0$) is given by

$$\mathbf{F}=G\Sigma_i \frac{M_i}{|\mathbf{r}_i|^3}\mathbf{r}_i, \tag{43}$$

where M_i denotes the mass of a typical "field star" and $\mathbf{r}_i$ its instantaneous position vector relative to the star under consideration. Further, in equation (43) the summation is extended over all the neighbouring stars. Our first question concerns the probability

$$W(\mathbf{F})dF_x\,dF_y\,dF_z = W(\mathbf{F})d\mathbf{F}, \tag{44}$$

that $\mathbf{F}$ occurs in the range $\mathbf{F}$, $\mathbf{F}+d\mathbf{F}$. By the application of a general method, due to Markoff, this probability distribution can be found. Thus measuring $\mathbf{F}$ in the units

$$Q_H=(\tfrac{4}{15})^{2/3}2\pi G(\overline{M^{3/2}})^{2/3}N^{2/3}=2{\cdot}603G(\overline{M^{3/2}})^{2/3}N^{2/3}, \tag{45}$$

where N denotes the number of stars per unit volume, and writing

$$\mathbf{F}=Q_H\boldsymbol{\beta} \quad \text{and} \quad |\mathbf{F}|=Q_H\beta, \tag{46}$$

it can be shown that

$$W(\boldsymbol{\beta})=\frac{1}{2\pi^2\beta^3}\int_0^\infty e^{-(x/\beta)^{2/3}}x\sin x\,dx. \tag{47}$$

The integral on the right-hand side of this equation has been evaluated numerically for various values of β, thus specifying the distribution function for $\mathbf{F}$.

To answer the remaining questions concerning the statistics of the gravitational field we have to consider the joint distributions of $\mathbf{F}$ and one or other of the following quantities:—

$$\frac{d\mathbf{F}}{dt}=G\Sigma_i M_i\left\{\frac{\mathbf{V}_i}{|\mathbf{r}_i|^3}-3\frac{\mathbf{r}_i(\mathbf{r}_i\cdot\mathbf{V}_i)}{|\mathbf{r}_i|^5}\right\}, \tag{48}$$

$$\mathbf{F}(t)=G\Sigma_i M_i\frac{\mathbf{r}_i+\mathbf{V}_i t}{|\mathbf{r}_i+\mathbf{V}_i t|^3}, \tag{49}$$

and

$$\mathbf{F}_1=G\Sigma_i M_i\frac{\mathbf{r}_i-\mathbf{r}_1}{|\mathbf{r}_i-\mathbf{r}_1|^3}. \tag{50}$$

In equations (48) and (49) $\mathbf{V}_i$ denotes the velocity of the field star *relative* to the one under consideration. It is possible to discuss these joint probability distributions and obtain the various first moments of $\dot{\mathbf{F}}$, $\mathbf{F}(t)$ and $\mathbf{F}_1$ for given $\mathbf{F}$ and $\mathbf{v}$. However, as the analysis is too involved to be summarized here we shall content ourselves with the consideration of one particular problem which appears to have some general interest. The problem we have in mind relates to the stability of wide binary stars.

As is well known, binary stars have a tendency towards disruption caused by the tidal effects of the nearby stars. Now this tendency toward disruption can be estimated as follows. For a given separation between the stars there exists a definite distribution function $W(\mathbf{F}_0, \mathbf{F}_1)$ governing the probability that forces of intensities $\mathbf{F}_0$ and $\mathbf{F}_1$, respectively, will act simultaneously on the two components of the binary. In other words, a differential acceleration governed by a definite probability law will operate on the system, which will tend to accelerate one star relative to the other. More particularly

$$\Delta F_{\parallel} = (\mathbf{F}_0 - \mathbf{F}_1) \cdot \mathbf{1}_{\mathbf{F}_0}, \tag{51}$$

where $\mathbf{1}_{\mathbf{F}_0}$ is a unit vector parallel to the direction of $\mathbf{F}_0$, represents the amount by which the star "0" will be systematically accelerated relative to the star "1". It is clear that it is this systematic acceleration of one component relative to the other which will be chiefly responsible for such changes in the orbital elements as may be effected. The average net increase in the velocity of the star "0" relative to the star "1" during a time Δt, long compared to the periods of the elementary fluctuations in $\mathbf{F}$, will therefore be given by

$$\overline{\Delta v}_{0,1} = \overline{\Delta F_{\parallel}} \Delta t. \tag{52}$$

The theory of the correlation of the forces acting simultaneously at two points separated by a finite distance, which we have outlined, enables the explicit evaluation of $\overline{\Delta F_{\parallel}}$. The formulæ simplify considerably when we consider separations which are less than a fifth of the average distance between the stars. Under these conditions equation (52) reduces to

$$\overline{\Delta v}_{0,1} = 4\pi G \bar{M} N a \Delta t, \tag{53}$$

where a denotes the separation. Since the mean square velocity of a star in its relative orbit is given by

$$\overline{V^2} = G(M_1 + M_2)/a, \tag{54}$$

where M_1 and M_2 denote the masses of the two components and a the semi-major axis of the orbit, we may *define* the time of dissolution, τ, of a binary by the equation

$$\overline{\Delta v}_{0,1} = (\overline{V^2})^{1/2}, \tag{55}$$

or using equation (53) we have

$$\tau \simeq \frac{(M_1 + M_2)^{1/2}}{4\pi G^{1/2} \bar{M} N a^{3/2}}. \tag{56}$$

From this formula it appears that the time of dissolution of binaries with semi-major axes between 10^3 to 10^4 astronomical units lies in the range 7×10^{10} to 2×10^9 years. And since, according to Ambarzumian, we can infer from the distribution of the semi-major axes of binaries that conditions of equipartition have not been attained in the galaxy, we may conclude that the time scale cannot exceed 3×10^9 years by any very large factor.

Bibliography :

1. S. Chandrasekhar, *Ap. J.*, 94, 511, 1941; 99, 25, 47, 54, 1944. Also *Annals of the New York Academy of Sciences*, 45, 131, 1943, and *Rev. Mod. Phys.*, 15, 1, 1943.
2. S. Chandrasekhar and J. von Neumann, *Ap. J.*, 95, 489, 1942; 97, 1, 1943.
3. V. A. Ambarzumian, *Russian Astro. J.*, 14, 207, 1937. Also *Nature*, 137, 537, 1936.

IV. Lindblad's Theory of Spiral Structure in Nebulæ

As is well known, Lindblad's theory of spiral structure in nebulæ derives from his theorem that circular orbits at the edges of highly flattened systems will be dynamically unstable. Thus, as he showed several years ago, circular orbits at the periphery of a homogeneous oblate spheroid will be unstable if the eccentricity of the spheroid is greater than 0·834 and that, moreover, stars describing such orbits will, on slight perturbations, depart from the edges along trajectories having a spiral character. There can be hardly any doubt that stars at the edges of more highly elliptical systems must be describing orbits near instability and that this instability must be of considerable significance for the future development of such systems. But it appears a difficult matter to trace in detail the various consequences which the instability we have described may lead to and, in particular, to decide as to whether the points at which material will depart along the spiral orbits will be at rest in space or at rest in a frame of reference rotating with the system. In this connection, Lindblad appeals to Bryan's theorem that Maclaurin spheroids first become unstable at an eccentricity $e = 0{\cdot}953$ for sectorial harmonic waves which have two opposite maxima. But it is hard to visualize how theorems valid for rotating homogeneous incompressible fluids can be applied to stellar systems with times of relaxation which may be as high as 10^{14} years. However, Lindblad presents a variety of arguments to support his view that the points of ejection must be fixed in space and that in consequence the winding of the spiral arms must be such that they are described outward in the direction of rotation. In particular, Lindblad believes that his photometric studies of NGC 7331 in different colours, as well as the polarization measurements of Öhman in the Andromeda nebula, confirm his conclusions regarding the sense of rotation. But Hubble and Mayall, discussing similar (and sometimes the same) material, come to exactly the opposite conclusions. The matter clearly requires further investigations both on the theoretical and on the observational sides.

Bibliography.—A general account of Lindblad's theory, together with a fairly complete list of his writings up to 1941, will be found in

1. S. Chandrasekhar, *Principles of Stellar Dynamics*, Chapter IV, pp. 152–180 and 191, 1942.

Later references are:

2. B. Lindblad, *Stockholm Obs. Ann.*, **13**, No. 10, 1941; **14**, No. 1, 1942.
3. Y. Öhman, *Stockholm Obs. Ann.*, **13**, No. 11, 1941.
4. E. Hubble, *Ap. J.*, **97**, 112, 1943.

S. CHANDRASEKHAR.

SOLAR ACTIVITY

Sunspots.—The provisional mean sunspot number (Greenwich) for the year 1944 was 10, as compared with the final Zürich figures of 16·3 for 1943 and 30·6 for 1942. The smoothed curve of spot frequency, falling continuously during 1942 and 1943 until May or June 1944, has now begun to rise. The epoch of minimum of the nearly completed 11-year cycle may thus be put provisionally as 1944·5, the epochs of the two previous minima being 1933·8 and 1923·6. It is of interest that so near to the present minimum as April 16, an extensive eruptive prominence rising 14′ above the Sun's limb, but with a terminal velocity of only 25 km./sec., was observed at Mount Wilson (*P.A.S.P.*, **56**, 124, 1944). Chromospheric activity observed on the Sun's disk on June 15, where a few small sunspots had previously been in latitude S. 25°, included velocities in the line of sight of 150 km./sec. outwards (Worthing observations: *Observatory*, **65**, 249, 1944).

During the year some 48 groups of sunspots were recorded on the Greenwich plates (242 days represented), and of these groups, which were mostly small, two-thirds were in latitudes which at this epoch of the cycle are distinctively those of new-cycle spots. Confirmation comes from the Mount Wilson observations of the magnetic fields of sunspots given in *P.A.S.P.*, **56**, 204, 1944, where the statement is also made that "the reversal of magnetic polarities in passing from the old cycle to the new cycle has again been observed".

These indications that the new cycle has now definitely commenced is strengthened by the recent appearance of a naked-eye group of spots in latitude S. 22°. This group crossed the disk between December 8 and 20, having its maximum area of over 1000 millionths of the Sun's hemisphere before central meridian passage on December 14·3. So far, no observations of special activity, relating to this group, have yet come to hand, but from the occurrence of radio fade-outs on December 10–15 it may be inferred that one or more major solar flares did occur. On December 16 a "great" magnetic storm was recorded at Abinger.

The 27-day sequence of magnetic disturbances that had been a conspicuous feature of 1943, in spite of the impending solar minimum, died out by the middle of 1944—another indication that the minimum had been reached by then (*Observatory*, *loc. cit.*). The recent magnetic storm of December 16–17 seems the first notable geophysical manifestation of the new 11-year cycle of solar activity. H. W. NEWTON.

Prominences.—The year 1944 has witnessed a further decline in all forms of solar activity.

The mean daily areas and numbers of calcium prominences as derived from Kodaikanal photographs are as follows:—

	Areas			*Numbers*		
	North	South	Total	North	South	Total
1944 January to June ...	0·98	1·13	2·11 sq. mins.	4·06	3·55	7·61
July to December ...	0·94	0·96	1·90 ,,	3·68	3·95	7·63

When compared with the previous year's figures, there is a decrease both in areas and numbers, the former being 23 per cent. and the latter about 20 per cent.

Both the areas and numbers show a southern preponderance. The distribution in areas and numbers show a maximum activity between 10°–15° and 35°–40° in the northern and 5°–10° and 45°–50° in the southern hemisphere.

Thirteen metallic prominences were observed during the year. Of these, 8 were in the northern and 5 in the southern hemisphere.

Eighteen displacements of the hydrogen *C* line in the chromosphere and prominences were observed during the year in the spectroscope. Of these, 11 were towards violet and 7 towards red.

SOLAR ACTIVITY—(*continued*)

Twenty-five displacements in prominences were observed with the spectrohelioscope as against 86 during the previous year. Of these, 14 were on the north and 11 on the south, while 13 were in the east limb and 12 in the west limb.

An eruptive prominence photographed on April 15 in the east limb, reached a maximum height of 4 minutes.

COMETS

During the year 1944 three new comets have been discovered and one periodic comet has been detected. A comet discovered by Berry at Dunedin on September 13 has not been included in the list as nothing further has been heard about it. The international situation is still responsible for a certain amount of delay in announcing discoveries and elements of orbits, when such have been computed.

Elements of the Orbits of Comets

Comet	T(U.T.)	ω	Ω	i
Schaumasse	1943 Dec. 1·457	50 59 07	86 44 28	12 00 01
Väisälä	1944 Dec. 27·814	238 46 00	28 53 00	16 42 00
Dutoit	1944 June 17·49027	257 00 39·6	22 22 55·0	18 45 08·4
van Gent	1944 July 17·67367	337 00 11·1	202 43 24·4	95 00 56·3

DOUBLE STARS

New Pairs.—Rossiter (*Publ. Obs. Univ. Michigan*, **9**, No. 1) has published his fifth list of new Southern Double Stars. Kuiper (*Ap. J.*, **97**, 275) gives 6 new binaries with large proper motion. Luyten (*Ap. J.*, **100**, 202) has a note on the double white dwarf LDS 275. Leonard (*P.A.S.P.*, **55**, 241) announces the duplicity of BD $-1°4043$. Joy and van Biesbroeck (*P.A.S.P.*, **56**, 123) give five new double stars among variables of the T Taur class and van Biesbroeck (*A.J.*, **51**, 61) gives a new companion to Wolf 1055 as the star of lowest known luminosity.

Measures.—Hirst (*M.N.*, **103**, 331) gives micrometer measures with the Cape 7-inch and Johannesburg 26½-inch refractors, Wesselink (*B.A.N.*, No. 341) photographic measures with the Yerkes 40-inch, and Brouwer and Jenkins (*A.J.*, **51**, 54) measures of Σ2398 on parallax plates with the same refractor.

Orbits.—Hirst (*M.N.*, **103**, 337 and 344) computes orbits for ADS 16497 and Melb. 4 AB, and gives a method of applying differential corrections. Campa (*Mem. Soc. Ast. Ital.*, **14**, No. 4) gives an orbit for ADS 7744, Gennaro (*Publ. Padova Obs.*, 66) for ADS 9494, Durham (*A.J.*, **50**, 165) for ADS 10087, and Alden (*A.J.*, **51**, 59), from measurements on parallax plates, for δ Aquilæ.

Miscellaneous.—van de Kamp and Strand (*A.J.*, **51**, 7 and 12) give notes on the astrometric study of unseen companions of single and double stars. Leonard (*P.A.S.P.*, **56**, 38, 85 and 202) determines the spectra of ADS 2894 and 12882. Wallenquist (*Arkiv Mat. Astr. Fys.*, **30A**, No. 8) publishes photometric observations of double stars. Schilt (*A.J.*, **51**, 189) gives some remarks about the mass ratios of *Castor* and 70 Ophiuchi.

W. H. VAN DEN BOS.

SOLAR ACTIVITY—(*continued*)

The mean daily area of hydrogen absorption markings (without foreshortening correction) was 1001·2 millionths of the Sun's visible hemisphere as against 1704 millionths during 1943, showing a marked decrease of 41 per cent. The distribution of areas in latitude shows a maximum activity between 40°–45° in the northern and between 45°–50° in the southern hemisphere. A. L. NARAYAN.

COMETS (*continued*)

Comet Schaumasse was observed from March 24 to 30 by Giclas at Flagstaff Observatory, and as a result a correction $\Delta T = +27^{d}$ was made to the assumed date of perihelion given in *Handbook, B.A.A.*, 1944.

Observed during 1944

Comet	q	Period (years)	Equinox	Computers	References
Schaumasse	1·19408	8·15478	1950·0	Sumner	*I.A.U. Circ.*, 984 *Handbook, B.A.A.*, 1944
Väisälä	2·3590	...	1944·0	Baur	*I.A.U. Circ.*, 986 *H.A.C.* 691
Dutoit	1·27714	14·868	1944·0	Bobone	*I.A.U. Circ.*, 988 *H.A.C.* 686, 689, 692
van Gent	2·22534	...	1944·0	Bobone	*H.A.C.* 686, 688, 693

M. DAVIDSON.

ADDRESS

Delivered by the President, Professor E. A. Milne, on the Award of the Gold Medal to Professor Bengt Edlén, Professor of Physics in the University of Lund

The Council has awarded the Society's Gold Medal to Professor Bengt Edlén for his identification of the origin of the principal lines in the coronal spectrum.

It has sometimes been the practice of the Royal Astronomical Society to award its Gold Medal, the highest distinction in its power, in recognition of a life's work devoted to astronomy. At other times the Society has used the award of the Gold Medal to recognise a particular piece of outstanding work. On this occasion the Society is following the latter course, and is honouring the discoverer of the solution of one of the outstanding problems of solar physics. The recipient of our Gold Medal this year is Dr. Bengt Edlén, whose experimental and theoretical work was done largely in the Physical Institute of the University of Uppsala, but who has recently been appointed, most appropriately, to the Chair of Physics, formerly held by Rydberg, in the University of Lund.*

The principal line in the Earth's auroral spectrum, the green line λ 5577·35, had been produced in the laboratory by McLennan and Shrum † in 1925, and shown to be due to atomic oxygen. The term-levels from which it originates were shown by Hopfield ‡ in 1927 to be associated with the ultra-violet lines $\lambda\lambda$ 1217·62, 999·47 of the *O*I spectrum; the difference between these lines corresponds to a wave-number of 17925·6 cm.$^{-1}$, whereas the auroral line λ 5577·35 corresponds to a wave-number of 17924·7 cm.$^{-1}$. Further discussion of the physical origin of this line was given in 1928 by Cario.§ It is now known to be due to the forbidden transition $^1D_2 - {}^1S_0$ amongst the levels of *O*I, neutral oxygen. Thus the suppositious element "geo-coronium" was disposed of. It had been so named by analogy with the so-called "coronium" lines in the spectrum of the Sun's corona, but at that time no similar success attended inquiry into the origin of the unknown coronal lines.

To put Edlén's work in its proper setting, it is necessary to mention again the year 1927. In October of that year, in *Nature* ‖, I. S. Bowen published his since famous discovery of the origin of the so-called "nebulium" lines—that is, the unclassified lines in the spectra of the gaseous nebulæ. His definitive paper was published in the *Astrophysical Journal* ¶ for January 1928. He showed, more particularly in the latter paper, that the nebulium lines, which are of course *emission* lines, were due to forbidden downward transitions from metastable levels in ionized oxygen and nitrogen atoms. For example, there is a well-known pair in the ultra-violet, at wave-lengths $\lambda\lambda$ 3729, 3726, these being the strongest ultra-violet lines. Bowen pointed out that in position and separation this pair agreed with the forbidden transitions of type $^4S - {}^2D$ in the spectrum of once-ionized oxygen, *O*II. In the same way he showed that the well-known pair in the green, $\lambda\lambda$ 5007, 4959, usually called N_1 and N_2, could be attributed to forbidden transitions of the type $^3P - {}^1D$ of doubly ionized oxygen, *O*III. The line λ 4363 could be attributed to the transition $^1D - {}^1S$ amongst the levels of the *O*III spectrum also. The pair in the red, $\lambda\lambda$ 6584, 6548, could be attributed to the forbidden transitions of

* See *The Observatory*, 65, 252, 1944.
† McLennan and Shrum, *Proc. Roy. Soc.*, 108, A, 501, 1925.
‡ Hopfield, *Phys. Rev.*, 29, 923, 1927.
§ Cario, *Journ. Franklin Inst.*, 205, 515, 1928.
‖ I. S. Bowen, *Nature*, 120, 473, 1927.
¶ *Ap. J.*, 67, 1, 1928.

type $^3P - {}^1D$ of once-ionized nitrogen, *N*II. In this way, Bowen accounted for almost all of the previously unidentified nebular lines. I append his list given in his letter to *Nature*:

λ	Origin	Transition	λ	Origin	Transition
7325·0	*O*II	$^2D - {}^2P$	4958·91	*O*III	$^3P_1 - {}^1D$
6583·6	*N*II	$^3P_2 - {}^1D$	4363·21	*O*III	$^1D - {}^1S$
6548·1	*N*II	$^3P_1 - {}^1D$	3728·91	*O*II	$^4S - {}^2D_3$
5006·84	*O*III	$^3P_2 - {}^1D$	3726·16	*O*II	$^4S - {}^2D_2$

It is difficult to over-emphasize the importance of this fundamental work by Bowen. Previous to his work, it had been generally concluded from the evidence of the periodic table of the elements and the Rutherford-Bohr picture of the atom, so wonderfully confirmed and made precise by Moseley's work on the atomic numbers of the elements deduced from the X-ray spectra, that there was no room for an unknown element "nebulium" amongst the lighter elements. Lockyer's success in discovering helium on the Sun through its D_3 line before it was isolated terrestrially could not be expected to be repeated with "nebulium". It was therefore realised that the unexplained lines in the nebulæ must be due to atoms of familiar kinds in unfamiliar conditions. H. N. Russell suggested that this unfamiliar condition might be very low density.

It was Bowen who showed how very low density could promote the appearance of lines which could not be produced under laboratory conditions. I will quote his words: "One type of line, which would be possible only under conditions of very low density, is that produced by an electron jump from a metastable state. A metastable state may be considered to be one from which jumps are very improbable, *i.e.* one whose mean life before spontaneous emission is very long. Under laboratory conditions the mean time between impacts of a given atom with other atoms is, even in the most extreme cases, only 1/1000 second. Consequently an atom in a metastable state will, in general, be dropped down to a lower state by a collision of the second kind long before it will be able to return directly with the emission of radiation. In the nebulæ, however, where the mean time between impacts is variously estimated at from 10^4 to 10^7 seconds, such atoms will return spontaneously and radiate a line with the frequency corresponding to the difference in energy between the metastable state and the final state. Since the probability of emission of these lines is very small, the probability of their absorption must also be very small. Thus the lines should not be observed in absorption".

He then went on to point out that hydrogen, helium, carbon, nitrogen, oxygen are the only elements known to exist in the gaseous nebulæ; that *C*I, *N*I, *N*II, *O*I, *O*II, *O*III are the only ions of these elements that have metastable states so placed that jumps from them would give rise to lines in the region of wave-lengths that is observable in nebulæ. But the degree of excitation in the nebulæ is such that neutral carbon, nitrogen and oxygen could be eliminated. There remained therefore as possible ions *N*II, *O*II and *O*III. A search by Bowen at once revealed that differences between known levels in these ions corresponded to observed emission lines in the nebulæ, as has been described above. This work was done in the Norman Bridge Laboratory of Physics, in the California Institute of Technology, Pasadena, in 1927.

Bowen's explanation was rounded off by Eddington *, who in December 1927 showed that to Bowen's condition of low density must be added the further condition that the stimulating radiation must be so weak that the atom is unlikely to absorb a quantum during the full duration of the metastable state. For otherwise the atom in the metastable state would absorb before it had time to emit its forbidden line.

Bowen's work enormously increased the expectation that the other well-known group of unexplained lines in celestial spectra, namely the so-called "coronium" lines in the spectrum of the solar corona, would soon be similarly accounted for, though Eddington's supplementary condition, owing to the intensity of the Sun's radiation passing through

* *M.N.*, 88, 134, 1927.

the corona, made such an explanation less possible. However, the auroral line and the nebular lines were seen to be physically akin. But there, for a long time, success ended. The unknown lines in the solar corona, especially the famous line λ 5303 in the green, obstinately refused explanation. It still seemed to remain probable that the "coronium" lines were due to light atoms in a moderate state of ionization. But the actual explanation, when it came, was something very different.

The actual level of excitation in the Sun's reversing layer is of the order of 6–7 volts, and it seemed unlikely that that in the corona would be higher. In the nebulæ, the excitation potentials corresponding to the metastable levels of Bowen's explanation are even smaller, amounting to 3·3 volts for the *O*II pair, $\lambda\lambda$ 3729, 3726, to 2·5 volts for the N_1, N_2 pair $\lambda\lambda$ 5007, 4959 of *O*III, and to 1·9 volts for the *N*II pair $\lambda\lambda$ 6584, 6548, to which must be added the ionization potentials—35 volts for *O*II, 55 volts for *O*III and 30 volts for *N*II. There seemed to be no likelihood of excitation or ionization potentials of a different order of magnitude being in question for the corona, and search was made, though without success, amongst the levels of the earlier stages of ionization of the lighter atoms in the hope of finding coincidences between the level-differences and the actual wave-lengths of the unexplained coronal lines.

Saha remarks in his recent paper * "On a physical theory of the solar corona" that he, and probably many others, "spent considerable time in ransacking the available literature for forbidden lines of elements which may coincide with some of the coronal lines, but without success". He adds that "the hunt was confined to only singly and doubly and sometimes trebly ionized atoms, because it was considered improbable that more highly ionized atoms can, without violating ordinary laws of physics, occur in the corona". It should be mentioned that the coronal lines occur only well outside the chromosphere, and extend to a considerable distance outside the Sun's limb, so that Bowen's condition of extreme tenuity is likely to hold good. It was, however, concluded by Swings even so late as 1939 † that the origin of the coronal lines remained as mysterious as ever.

The solar corona had been observed in ancient times, and is said by Young to be described by Philostratus and Plutarch much as we should describe it to-day. But the first solar eclipse to be scientifically observed and seriously described was that of 1842, for which the line of totality traversed Spain, France and Italy, and of which the results obtained were summarised by Arago in 1846.‡ It was not at this time established that the corona was a solar and not a lunar appendage, and for a time attention was chiefly concentrated on the prominences. Photography was employed for the first time at the eclipse of 1860, for which Secchi published a drawing of the corona. This was the year in which Kirchhoff § first applied the ideas of the complementariness of emission and absorption of radiation to the solar spectrum, and soon after that, in 1868, occurred the first applications of spectral analysis to the solar envelopes. The green emission line λ 5303 in the corona was discovered independently by Harkness and Young || at the eclipse of 1869. Curiously enough, this line was at first erroneously attributed by Kirchhoff and Ångstrom to the spectrum of iron, but it was later shown that the *Fe* line is the lower component of the line, which had been found to be double in 1876.¶ Since 1869, somewhat more than twenty relatively well-measured lines have been discovered which are specifically characteristic of the corona. Eleven of these were photographed,

* *Proc. Nat. Inst. Sci. India*, **8**, 99, 1942.

† Swings, *Scientia*, 1939, p. 69.

‡ *Annuaire du Bureau des Longitudes, Paris.* This information, together with other points in eclipse history, is extracted from Deslandres' *Histoire des Idées et des Recherches sur le Soleil* (published in the same *Annuaire* for 1906), a copy of which is in the writer's possession.

§ Poggendorff's *Annalen*, Bd. 109, 1860. The "Untersuchungen über das Sonnenspectrum" was first published in *Abh. Königl. Akad. Wiss.*, Berlin, 1861. My own copy is a reprint dated 1862.

|| Young, *The Sun* (1882), p. 224.

¶ Young, *loc. cit.*, p. 230.

five for the first time, by Lyot * without an eclipse, and their wave-lengths tabulated. None of these lines have been observed in any terrestrial source, or, until 1933, in any other celestial source. In that year, Adams and Joy † observed some characteristic coronal lines during the nova outburst of RS Ophiuchi.

The story of Edlén's identification of the origin of the coronal lines begins perhaps with Spencer Jones's observation ‡ of certain new unidentifiable lines in the later spectrum of Nova RR Pictoris 1925, in particular λλ 5723, 6087. These were described by Spencer Jones as forming the most interesting feature of the later spectrum of this nova. A suggested identification of λ 5723 with a forbidden line of *Fe*III by certain writers § was criticised by Swings and Edlén || on the ground that the supposed identification gave both the wrong wave-length and the wrong character to the line. This early betrayed Edlén's interest in unknown lines. In the following years he worked in the laboratory analysing many of the higher spark spectra of the elements with a vacuum spectrograph, publishing numerous papers in *Zeitschrift für Physik* on the subject. With Bowen he returned to the subject of Spencer Jones's lines in Nova RR Pictoris in 1939 in a letter to *Nature*.¶ In that communication, armed with Edlén's garnered experimental results, these writers attributed the unidentified lines λλ 5723, 6087 to forbidden transitions amongst the levels of the six-fold ionized iron atom, *Fe*VII. They gave the series classification as

$$\lambda\,5723, \quad {}^3F_2 - {}^1D_2,$$
$$\lambda\,6087, \quad {}^3F_3 - {}^1D_2.$$

The separation of λ 5723 and λ 6087 in wave-number showed them to have precisely the separation of the observed $^3F_2$ and $^3F_3$ levels of *Fe*VII. The agreement was found to be in fact very close.

The *Fe*VII ion has $26-6=20$ electrons, of which two lie outside the inner closed groups, as a pair of $3d$ electrons. These contribute the spectrum of the *Fe*VII ion. Starting with an arbitrary zero, the actual $3d^2$ levels located in the *Fe*VII spectrum were given as

$^3F_2$	0,	$^3P_0$	20037.
$^3F_3$	1047,	$^3P_1$	20428.
$^3F_4$	2327,	$^3P_2$	21275.
$^1D_2$	17475,	$^1G_4$	28916.

The corresponding calculated wave-lengths were given as

$^3F-{}^1G$,	λ 3457·3,	3587·2,	3759·9.			
$^3F-{}^3P$,	λ 4699·0,	4893·9,	4942·3,	4989·4,	5158·3,	5276·1.
$^3F-{}^1D$,	λ 5720·9,	6085·5,	6599·7.			

The list of lines observed in Nova Pictoris, of unknown origin, including the pair already mentioned, was

λ 3760·0, 4944·7, 5275·6, 4701·2, 4986·1, 5723·4, 4894·8, 5155·3, 6087·5.

Thus the *complete* array of *Fe*VII forbidden transitions in the region accessible to observation occurs in the spectrum of Nova Pictoris. Moreover, *all* the lines of hitherto unknown origin in the later stages of the spectrum of Nova Pictoris were accounted for. It was pointed out also that λ 6087 was also coincident with a line of *Ca*V. It is thus a

* *M.N.*, 99, 590, 1939.
† *P.A.S.P.*, 45, 301, 1933.
† *M.N.*, 94, 34 and 816, 1933–34.
§ *Proc. Nat. Acad. Sci.*, 19, 581, 1933.
|| *C.R.*, 198, 1842, 1934.
¶ I. S. Bowen and B. Edlén, *Nature*, 143, 374, 1939.

blend, and the difference in intensity-variations in time, between it and λ 5723, hitherto held to preclude a common origin for the two lines, could be held to be explained.

Thus Bowen and Edlén produced indisputable evidence that a higher level of excitation than had been previously supposed possible was present in at least some celestial spectra.

This letter to *Nature*, published 1939 March 4, was at once noticed by W. Grotrian, of the Astrophysikalisches Observatorium at Potsdam, and he sent a note * to *Die Naturwissenschaften*, dated 1939 March 16, of which I append a translation of the opening paragraph:

"Since the recent demonstration by I. S. Bowen and B. Edlén that forbidden lines of *Fe*VII have appeared in the spectrum of Nova RR Pictoris 1925, and since the occurrence of five coronal lines in the nova-like outburst of RS Ophiuchi in the year 1933 has been conclusively proved, and since finally signs are growing that in the outer zones of the Sun's atmosphere conditions for the stimulation of spectral lines appear to be present which far exceed what would be expected on thermal equilibrium, it seems to me no longer out of the way to discuss the question whether the coronal lines can be considered as forbidden lines of highly ionized atoms".

There we have the chain of argument explicitly stated. Grotrian then considered the coronal lines λ 6374 and λ 7892. Using Edlén's observations of term-values he suggested the following identifications:—

Coronal wave-length observed, λ 6374·51. Wave number observed $\nu = 15{,}683$ cm.$^{-1}$.
Attribution. *Fe*X, $3s^2 3p^5$, $^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}$, ν (calc.) = 15,685 cm.$^{-1}$.
Coronal wave-length observed λ 7891·94. Wave number observed $\nu = 12{,}668$ cm.$^{-1}$.
Attribution. *Fe*XI, $3s^2 3p^4$, $^3P_1 - {}^3P_2$. ν (calc.) = 12,675 cm.$^{-1}$.

Grotrian thus attributed λ 6374 to the nine-fold ionized iron atom, and λ 7892 to the ten-fold ionized iron atom.

Grotrian also pointed out that whilst the bright coronal line λ 5303 had a different intensity-distribution in the corona from λ 6374, λ 6374 and λ 7892 (Lyot's recently found line) had similar behaviours, thus suggesting confirmation of his identification with two highly ionized iron atoms in stages of ionization differing by only one electron.

It is clear that Grotrian's discovery of the wave-length coincidences between two coronal lines and forbidden transitions between *Fe*X and *Fe*XI levels was fundamentally important. It was a daring step to take, to suggest such highly stripped atoms as the source of any of the coronal lines.

As Edlén says in his paper of 1941 March 12 †, Grotrian's paper "gave the impulse to a systematic search for analogous term separations". Edlén was in a strong position to conduct such a search, having available his own observations of term-levels found for highly stripped atoms from his researches of several years with vacuum spectrographs. I shall follow the details given in Edlén's simpler preliminary paper mentioned above rather than in his definitive paper ‡ published later in *Zeitschrift für Astrophysik*, as the latter is only available in this country so far in microfilm form, though I have also consulted this latter.

Edlén at once found that two other coronal lines, namely λ 3328 and λ 4086, could be attributed to the $^2P_{\frac{3}{2}} - {}^2P_{\frac{1}{2}}$ and $^3P_2 - {}^3P_1$ transitions in the spectra of *Ca*XII and *Ca*XIII respectively, as given by his own unpublished measurements; that is to say, to the eleven-fold and twelve-fold ionized calcium atoms. This in turn suggested to Edlén that Grotrian's and his wave-length coincidences did not happen by chance, and that "the whole coronal spectrum might consist of forbidden lines analogous to those of gaseous

* *Naturwiss.*, **27**, 214, 1939. (Published 1939 March 31.)

† "An attempt to identify the emission lines in the spectrum of the solar corona", *Arkiv. für Mat., Astron. och Fys.*, Bd. 28 B, No. 1, 1941.

‡ *Zeits. für Astrophys.*, **22**, 30–64, 1942.

nebulæ but from atoms much more highly ionized than had previously been considered at all".

The ionization potentials for Grotrian's *Fe*X and *Fe*XI ions amounted to 233 volts and 261 volts respectively; those for Edlén's *Ca*XII and *Ca*XIII ions to 589 and 655 volts respectively (I take the figures from Edlén's published table). Now the kinetic energy of an electron falling through 500 volts corresponds to the mean energy of a particle at 3,800,000 degrees. The degree of excitation was therefore enormous compared with what would be expected in the vicinity of the Sun's surface.

The ions of *Ca*XII and *Fe*X are known as iso-electronic. This means not that they have the same numbers of electrons, but that they have the same numbers of electrons in the spectroscopically active part of the ion—the outer shell of electrons. This may be verified as follows. The atomic number of calcium is $Z=20$. The ion *Ca*XII has lost 11 electrons, and there thus remain 9. Of these the two innermost form the closed K-shell, consisting of two ($1s$) electrons, and the remaining seven are present as two ($2s$) electrons and five ($2p$) electrons. The atomic number of iron is $Z=26$. The ion *Fe*X has lost 9 electrons, and there thus remain 17. Of these the two innermost form the closed K-shell of two ($1s$) electrons, the next eight form the closed L-shell of two ($2s$) electrons and six ($2p$) electrons, and the remaining seven are present as two ($3s$) electrons and five ($3p$) electrons. Thus the *Ca*XII and *Fe*X ions each possess seven outer electrons, and are spectroscopically equivalent to the halogens.

Similarly *Ca*XIII and *Fe*XI are iso-electronic, each possessing 6 outer electrons. They are spectroscopically equivalent to once-ionized halogens. Their complete relations are shown in the following short table:—

Coronal Line	Ion	Z	Number of Electrons remaining	Arrangement	Transition	I.P. Volts
λ 6374·51	*Fe*X	26	17 = 2 + 8 + 7	$(1s^2)(2s^22p^6)(3s^23p^5)$	$^2P_{\frac{3}{2}} - {}^2P_{\frac{1}{2}}$	233
λ 3328·1	*Ca*XII	20	9 = 2 + 7	$(1s^2)(2s^22p^5)$	$^2P_{\frac{3}{2}} - {}^2P_{\frac{1}{2}}$	589
λ 7891·94	*Fe*XI	26	16 = 2 + 8 + 6	$(1s^2)(2s^22p^6)(3s^23p^4)$	$^3P_2 - {}^3P_1$	261
λ 4086·29	*Ca*XIII	20	8 = 2 + 6	$(1s^2)(2s^22p^4)$	$^3P_2 - {}^3P_1$	655

Unfortunately Edlén had no more *observed* term-differences giving lines in the observable region at his disposal. He therefore proceeded to predict by extrapolation term-differences likely to be found in the corona according to those already found. The prediction was by iso-electronic sequences, *i.e.* by considering a sequence of spectra derived from ions having the same outer configurations of electrons. Edlén's own work on ultra-violet spectra, published at length in various papers in *Zeitschrift für Physik* gave him the required data.

He argued that there were good reasons to expect intense lines of the ions *Fe*XIII and *Fe*XIV because, first, of the rich abundance of iron as judged from the intensity of *Fe*X and *Fe*XI, secondly because an intense degree of ionization was expected to be possible, since the *Ca*VII lines of Nova Pictoris * were absent, whilst the I.P.'s of *Ca*XII and *Ca*XIII were much higher than the I.P.'s of *Fe*X and *Fe*XI, as stated above. Now the I.P.'s of *Fe*XIII and *Fe*XIV are 325 volts and 355 volts, and so intermediate between the two groups just mentioned. It was at once found that the extrapolated separation in the ground term of *Fe*XIV (which has three outer electrons) corresponded to the strongest and best-known line in the coronal spectrum, λ 5303, and that the three next strongest coronal lines $\lambda\lambda$ 10,747, 10,798 and 3388 corresponded to transitions of the ion *Fe*XIII (four outer electrons). In addition, the fainter line λ 3987 could be attributed to another transition in the *Fe*XI ion already found by Grotrian, namely the transition $^3P_1 - {}^1D_2$. Thus altogether, the *Fe*X, XI, XIII and XIV identifications comprised more than nine-tenths of the total coronal emission. The ion *Fe*XII is missing because the

* *V. supra.*

extrapolated *Fe*XII transitions are unobservable, and none of *Fe*VIII, IX, XV, XVI, XVII have any deep-lying metastable levels.

Accepting these identifications, it was then possible to examine the corresponding transitions in the neighbouring elements in the periodic table. The element *nickel* has atomic number $Z = 28$, and the ions *Ni*XII, XIII, XV, XVI possess in their outer configurations 7, 6, 4, 3 electrons respectively, and so are iso-electronic with *Fe*X, XI, XIII, XIV respectively. The complete set of transitions extrapolated to *Ni* was now found in the remaining coronal lines with the same relative intensities as for *Fe*, though with much smaller absolute intensities. This identified 6 more coronal lines. The *Fe* lines were on the average about 10 times as strong as the corresponding *Ni* lines. The suggested identifications agreed, moreover, well with Lyot's intensity-groupings. The nickel identifications accounted for a further 7 per cent. of the total coronal emission, leaving less than 3 per cent. of the total emission unidentified.

The elements potassium, chromium, manganese and cobalt, of atomic numbers $N = 19, 24, 25, 27$, which might have been expected to be present in the corona, are unrepresented, save possibly for a very faint line attributed by D. Kundu (1941) to *Co*XV. Edlén suggested in consequence that these elements are effectively absent; and he pointed out that if the corona consists principally of calcium, iron and nickel, it corresponds in composition to the average composition of the stony and iron meteorites. The suggestion would be that the coronal gases are formed by the vaporization of inward-falling meteoritic dust. However, this suggestion is considered by Saha to be untenable, on the ground that the coronal lines *widen* as we pass inwards, whereas owing to resistance the meteoritic velocity would be expected to *diminish* inwards. Further, Saha considered it could be shown that an iron atom vaporized from a meteor striking the Sun with the velocity of free fall (600 kms. sec.$^{-1}$) could not be relieved of as many as 14 electrons whilst passing to the inner corona. Saha has been hence led to attribute the high state of ionization found by Grotrian and Edlén in the corona to some kind of nuclear reaction, similar to uranium fission, occurring within the Sun's reversing layer or chromosphere, the formation of the outer corona being ascribed to the constant stream of δ-rays ejected from the solar atoms by the high-speed ions.

This theory involves an *ad hoc* hypothesis and can hardly yet be considered convincing. The problem of the origin of the coronal ionization remains. The old objection to the possibility of the coronal lines being originated as forbidden transitions on the ground that the intense solar radiation would quickly raise the metastable states to higher levels and so leave insufficient time for a natural emission is, however, now removed; for the metastable levels in question are such that to excite them the exciting radiation would have to be in the soft X-ray region, where the Sun's radiation may be expected to be weak.

Since the corona can have only a slight excess of negative charge, the presence of these so highly ionized atoms must be accompanied with an atmosphere of free electrons to neutralise it, the partial pressure of free electrons being of the order of a dozen times the partial pressure of the atoms. These free electrons may account for the continuous spectrum of the corona. An extensive distribution of free electrons in the corona used to be frequently suggested, more especially by Wilhelm Anderson of Dorpat. Edlén's work gives the justification.

However, it is not my duty to-day to go further into the physical state of the corona, but to emphasize to you the splendid success of Dr. Bengt Edlén in following up his experimental researches in vacuum-spark spectroscopy with this brilliant attribution of the coronal lines to highly ionized atoms of iron, calcium and metal. I append a list, in continuation of my former table, of the remaining identifications, adapted from Edlén's paper. Ions with the same electronic arrangement give rise to spectroscopically similar lines. Thus the analogue of the green line λ 5303, due to thirteen-fold ionized iron, with three outer electrons, is the ultra-violet line λ 3600·97, attributed to fifteen-fold ionized

Coronal Line	Ion	Z	Number of Electrons remaining	Arrangement	Transition	I.P. Volts
λ 3986·88	*Fe*XI	26	16 = 2 + 8 + 6	$(1s^2)(2s^22p^6)(3s^23p^4)$	$^3P_1 - {}^1D_2$	261
λ 3388·10	*Fe*XIII	26	14 = 2 + 8 + 4	$(1s^2)(2s^22p^6)(3s^23p^2)$	$^3P_2 - {}^1D_2$	325
λ 10746·80	*Fe*XIII	26	14 = 2 + 8 + 4	$(1s^2)(2s^22p^6)(3s^23p^2)$	$^3P_0 - {}^3P_1$	325
λ 10797·95	*Fe*XIII	26	14 = 2 + 8 + 4	$(1s^2)(2s^22p^6)(3s^23p^2)$	$^3P_1 - {}^3P_2$	325
λ 5302·86	*Fe*XIV	26	13 = 2 + 8 + 3	$(1s^2)(2s^22p^6)(3s^23p)$	$^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}$	355
λ 4231·4	*Ni*XII	28	17 = 2 + 8 + 7	$(1s^2)(2s^22p^6)(3s^23p^5)$	$^2P_{\frac{3}{2}} - {}^2P_{\frac{1}{2}}$	318
λ 3642·87	*Ni*XIII	28	16 = 2 + 8 + 6	$(1s^2)(2s^22p^6)(3s^23p^4)$	$^3P_1 - {}^1D_2$	350
λ 5116·03	*Ni*XIII	28	16 = 2 + 8 + 6	$(1s^2)(2s^22p^6)(3s^23p^4)$	$^3P_2 - {}^3P_1$	350
λ 6701·83	*Ni*XV	28	14 = 2 + 8 + 4	$(1s^2)(2s^22p^6)(3s^23p^2)$	$^3P_0 - {}^3P_1$	422
λ 8024·21	*Ni*XV	28	14 = 2 + 8 + 4	$(1s^2)(2s^22p^6)(3s^23p^2)$	$^3P_1 - {}^3P_2$	422
λ 3600·97	*Ni*XVI	28	13 = 2 + 8 + 3	$(1s^2)(2s^22p^6)(3s^23p)$	$^2P_{\frac{1}{2}} - {}^2P_{\frac{3}{2}}$	455

nickel, also with three outer electrons. This is the strongest of the lines attributed to nickel, according to Grotrian's intensity measures *, being of estimated intensity 12 on a scale on which λ 5303 was 20.

We have with us a representative of the Swedish Legation, and I have great pleasure in handing him the Society's Gold Medal, for transmission to Professor Edlén. With it we offer our hearty congratulations to Professor Edlén on the achievement of the identification, in an unexpected way, of the principal unknown lines in the Sun's coronal spectrum, coupled with the best wishes for his future researches and the earnest hopes that these researches will continue to aid in the solution of the fascinating problems they have opened up.†

* Grotrian, *Zeits. für Astrophys.*, **2**, 106, 1931.

† In preparing this address, I have been indebted to Prof. H. H. Plaskett for several references; and also to an article by Dr. A. Hunter, "Solar Physics," in *Reports on Progress in Physics*, **9**, 101, 1943.

ADDRESS

Delivered by the President, Professor E. A. Milne, on The Natural Philosophy of Stellar Structure

In November of last year we lost by an unexpectedly early death one who was by universal consent a great astronomer and a great natural philosopher. The death of Sir Arthur Eddington cannot but cast a gloom over our proceedings to-day. We lament a lost leader, one who led us to the mountain-tops of scientific vision, who with aquiline sight pierced the distant mists and described to us distant landscapes and prospects long before we lesser mortals could view them ourselves. Mathematician, physicist, astronomer, philosopher, he made mathematical physics, astronomy and philosophy into a single integrated whole, into natural philosophy indeed. He was gifted with superb physical insight; he must often have reached his mathematical results by physical arguments before he had constructed the mathematical proofs, and his vigorous marshalling of his syllogisms would carry his audiences with him over most formidable mathematical ground. We can even now recapture the thrills he evoked when he unfolded his researches, if one re-reads, as I have done lately, some of his pioneer papers.

There is a famous parenthesis in *The Internal Constitution of the Stars* in which he tells us his own views on the relation of physical insight to mathematical proof. Physical insight he defined as the seeing "which of the numerous factors are particularly concerned in any effect, and how they work together to give it". And in an eloquent phrase he pointed out that "a legitimate approximation is not just an unavoidable evil; it is a discernment that certain factors do not contribute appreciably to the result". "This discernment is only a continuation of a task begun by the physicist before the mathematical premises of the problem could be stated". He went on to write of the process of selection, amidst actual conditions of extreme complexity, of those which have an essential influence on the result. He admitted that, if challenged, the physicist must be prepared to defend the use of his discernment, with the proviso that unless the defence involved some subtle points of difficulty, the defence could be left until the challenge is made. He concluded his aside by asserting that for the mathematician, insight is one of the tools, proof the finished product, but for the physicist proof is one of the tools, insight the finished product. "The tool must not usurp the place of the product, even though we fully recognise that disastrous results may occur when the tool is badly handled".

It is with a disaster of this kind that I wish to deal later in this address.

Eddington's marvellous flair for anticipating by physical insight results later arrived at by detailed analysis is illustrated again and again in his studies of stellar structure. That branch of investigation is only one of the many subjects he illuminated and adorned, but it is one which seems at present most securely accepted. If ever a man *created* a new field of research, Eddington created the field of stellar structure as a living study in physics. Though Eddington made plentiful and generous use of the work of his predecessors, in particular Homer Lane and Emden, by comparison their contributions, important as they were, read like academic exercises. Eddington's stars were made of real matter, of the stuff that physicists experiment with; and it is impossible to overestimate the significance of his researches in persuading physicists that the laws they had discovered could safely be extrapolated to the enormous temperatures and pressures ruling in stellar interiors. If astronomy owes many a debt to physics, physics owes to astronomy, and largely to the astronomer Eddington, the recognition that the interiors of stars can be regarded as high temperature laboratories.

As an instance of his physical insight, I may mention his successive conclusions that ρ/T^3 is approximately constant inside any one star, that the mass absorption coefficient k is approximately constant from star to star, and that these and other results could be harmonised if he assumed as a physical law $k \propto \rho/T^3$; these being followed by his triumphant vindication that, apart from what he called a guillotine factor, $k \propto \rho/T^{7/2}$—a result amazingly close to his original conjecture. But the whole march of these researches —his original discovery that radiation pressure was of importance, his calculation of the flux of radiant energy in terms of the gradient of radiation pressure, his dogged pursuit of the consequences of the perfect gas hypothesis, ending in his discovery of the mass-luminosity law—all these exhibited a mastery guided by sure instinct that rightly demands our admiration.

I have said that Eddington's results in the field of stellar structure seem to be generally accepted to-day. Yet many of them, both when first announced and on later occasions, were seriously challenged in his lifetime. Before he died, I had planned that this my concluding Presidential Address should attempt to discuss some problems in the natural philosophy of stellar structure, and I had fully expected that in his presence I should have an opportunity of putting forward my difficulties on the subject. I think that in these gloomier circumstances he would not have me desist. I feel that in spirit he is still with us, and that the best and most honest tribute I can pay to his influence is to trace the emergence in his papers of his specific views, and to try to show where I think alternative views are possible.

I am the more emboldened to attempt this in that three years ago, in 1942 April, my predecessor Professor Sydney Chapman delivered a learned address on "The Source of the Sun's Energy", in which he presented the at present accepted views on stellar structure, but asked at the conclusion, with reference to the "possible and self-consistent" solution he had described: "Is it the actual and only possible solution, or can Milne be right in urging a quite different solution as possible and actual? I think the burden of proof, which seems to me to be no light one, must rest on him".

That is a challenge which I ought not to evade. But I want to make clear at the outset that I have in past papers expressed myself very badly if I have given the impression that I have a *completely* different solution of the problem of stellar structure to advocate. I accept much of what Eddington has concluded as regards conditions inside stars, and I humbly follow, and have always followed, his methodology. But that does not prevent my having serious difficulties with some of the conclusions he appears to reach by that methodology. To bring out wherein these difficulties lie, I beg to be allowed to re-trace the path which Eddington initially followed, and to attempt to show how it is possible (in his own words) to challenge on mathematical grounds some of the results he reached by his own bold use of physical insight.

In his first paper * in our *Monthly Notices* on this subject (1916 November) he propounded what, in one form or another, has come to be known as the *standard model* of a star. This is the model in which, in the first place, k the mass absorption coefficient and $4\pi\epsilon$, the rate of generation of energy per unit mass, are constant throughout the star; in the second place, the transfer of energy from centre to boundary is by the mechanism of radiation; and in the third place, the material is assumed to obey the laws of an ideal gas, of constant molecular weight μ, throughout. Eddington derived from these assumptions two fundamental formulæ, one of which determines the ratio of radiation pressure to gas pressure inside the star, and the other of which determines the luminosity of the star in terms of its mass. These formulæ are not stated in this, his pioneer paper, in the form in which they afterwards became classical; but they may be found stated in his wonderfully compact paper of two years later in the *Astrophysical Journal* † for 1918 November, in his classical notation. The formulæ in question are

* *M.N.*, 77, 16, 1916. † *Ap. J.*, 48, 205, 1918.

$$1-\beta=\text{const.}\times M^2\mu^4\beta^4, \tag{1}$$

$$L=4\pi cGM(1-\beta)/k, \tag{2}$$

where c denotes the velocity of light, G the constant of gravitation, M the mass of the star, L its absolute bolometric luminosity, and β denotes the ratio of gas-pressure to total pressure. I ask to be allowed to dwell on these formulæ for a short time.

It is true that Eddington introduced modifications into the second of these formulæ as he developed the subject. Of some of these modifications I may speak later. But in the above form they have had a tremendous influence on all subsequent writers on the subject of stellar structure; and, to my reading of the situation, they had a tremendous influence on Eddington himself. There is no doubt that the invention of the standard model of a star by Eddington marked an epoch in the development of the subject. By the simplicity and crispness of the assumptions behind it, it provided a supple and tractable instrument for comparison with observed stars: *supple*, as is shown by the ease with which Eddington extended its range; *tractable*, because an almost exact mathematical solution is possible.

This mathematical solution I have given in brief in the Appendix, section 1. The results there obtained are precisely Eddington's, but I have followed a direct method for obtaining the constant of proportionality in the quartic equation. The important point which emerges is that this constant of proportionality is a *boundary* value obtained by carrying through a numerical quadrature to the *boundary*. I want to make it clear that I fully accept Eddington's *solution* for this form of the standard model; I do not at this stage raise any questions about the appropriateness, in the context considered, of the boundary condition used, namely that the boundary is placed where to all intents and purposes the temperature vanishes.

But the physical result thus obtained is at first sight amazing and incredible. The mathematical formulæ appear to predict the luminosity—that is, the total generation of energy per second of a mass of gas M, in terms of its molecular weight μ, opacity coefficient k, and universal constants, in addition to M itself. They appear to predict from equilibrium considerations only, without any reference to atomic or sub-atomic processes of energy generation, exactly how much energy is generated per second by a given mass M. Small wonder that the correctness of this interpretation was disputed by Jeans. For clearly there is no physical obligation on the material to be evolving energy at just the rate predicted by the formula for L. Eddington wrote in 1916 November (*loc. cit.*, p. 20), "the simplest theory results if we suppose that the energy is produced by radio-active processes"; and he accordingly took the energy liberated to be at the rate of $4\pi\epsilon$ ergs per gram per second. His equilibrium theory appears at first sight to predict ϵ, which is clearly nonsense.

Now Eddington never seriously believed that the energy-generation in stars was of radio-active character. His remark quoted above was merely an illustration. Nevertheless, there is nothing logically wrong in making such an assumption and we are then led to a logical contradiction; for there is no necessity for ϵ to have the value predicted by the theory.

What is the explanation? The explanation is that the luminosity formula, with β determined by the quartic equation, is merely the *condition* that a mass of material, of given constant opacity k, generating energy at a constant rate $4\pi\epsilon$ per unit mass per second throughout its volume, can remain in the form of a perfect gas. Let $4\pi\epsilon$, the *actual* rate of generation of energy, differ to the slightest extent from the value L/M predicted for the standard model: then the material cannot exist in the form of a perfect gas configuration. A perfect gas configuration needs a unique value for $4\pi\epsilon$ to sustain it distended against its self-gravitation. If $4\pi\epsilon$ has some other value, the configuration must in some portion of its mass cease to follow the laws of a perfect gas.

The way in which it might be expected to re-arrange itself was the subject of my

papers on "The Analysis of Stellar Structure" of 1930, 1932.* I there reversed Eddington's procedure: I showed that the *actual* rate of generation of energy of the supposed model determines a numerical value for $[-\xi_0^2(d\theta/d\xi)_0]$ which will not in general coincide with Emden's value. It provides a value with which we may start an *inward* integration; and this inward integration will yield a density-distribution which either heads for a very large density (ultimately an infinite density) near the centre, or heads for a density-zero; and in the latter case the configuration would be bound to collapse on itself. It was shown that white dwarfs will be of the category of "collapsed" configurations. But I do not wish to go here into details concerning what I called "collapsed" and "centrally-condensed" configurations; and I am fully aware that authors of distinction have concluded that centrally-condensed configurations cannot exist in nature. What I wish to insist on here is that, on the same showing, neither can purely gaseous configurations exist in nature; that, to my mind, Eddington's interpretation of his analysis was illegitimate, the correct interpretation being, as stated, that the wholly gaseous model is an impossibility. We may not have been able to foretell the way in which nature evades the difficulty; but if the original standard model tells us anything at all, it tells us that in general wholly gaseous configurations will not be found in nature, for the simple reason that only by accident could a model of the kind considered generate energy at the rate required for equilibrium.

It may be objected that no one supposes a star to be built on the standard model. For one thing, the perfect gas standard model has an arbitrary radius, whilst the stars in nature have usually quite definite radii. I agree that the objection would be just. But it merely comes to another form of the same negative conclusion, namely that a mass of material cannot persist in nature satisfying the conditions that k and ϵ are constant throughout the star and that the material is wholly gaseous. It is reasonable to expect that nothing crucial is involved in supposing that the values to be taken for k and ϵ represent suitable mean values throughout the interior, whether actually constant or not; in that case, it is the perfect gas hypothesis which fails.

I have in the foregoing argued as though k were a known constant of the material, given beforehand. Of course k *might* adjust itself to the value appropriate to the luminosity, the star (for some reason best known to itself) endeavouring meanwhile to remain gaseous. I do not see why this adjustment should take place. But another objection to this possibility is that calculations of the theoretical value of k, such as those so brilliantly undertaken by Eddington, do not show it to be a particularly adjustable parameter. The atomic properties which control ϵ, and those which control k, are so essentially different, and relate to such distinct parts of the atom, that it would seem unnatural for k to adjust itself to ϵ merely in order that the star should remain gaseous throughout.

Eddington soon saw that the assumption at the base of this model could be widened. The equation of transfer of energy, to a sufficient approximation, can be written in the form

$$\frac{d(\frac{1}{3}aT^4)}{dr} = -\frac{k(r)L(r)}{4\pi r^2 c}\rho, \tag{3}$$

an equation which remains true whatever functions of r, k and L may be. Combining this in the usual way with the equation of mechanical equilibrium we get

$$\frac{d(\frac{1}{3}aT^4)}{d(p+\frac{1}{3}aT^4)} = \frac{k(r)L(r)}{4\pi cGM(r)}. \tag{4}$$

The absorption coefficient $k(r)$ occurs only in combination with $L(r)$, and Eddington pointed out that instead of assuming $k(r)$ and $L(r)/M(r)$ to be separately constant and

* *M.N.*, 91, 4, 1930; 92, 610, 1932.

independent of r, we need only assume the product of $k(r)$ and $L(r)/M(r)$ to remain constant and independent of r. Writing

$$\frac{L(r)}{M(r)} = \eta \frac{L}{M}, \tag{5}$$

the assumption is now that $k\eta$ remains constant as we traverse the material of the star. If $k\eta$ is constant, the luminosity is given by the formula

$$L = 4\pi cGM(1-\beta)/k\eta, \tag{6}$$

where β is constant and is given by the same quartic equation as before. This determines L as soon as the constant value of $k\eta$ is known.

The value of η is known at the boundary of the star only. At $r = r_0$, $L(r) = L$ and $M(r) = M$, and so here $\eta = 1$. If then k_0 is the value of k at the boundary, and if $k\eta$ is actually constant from centre to boundary, the luminosity formula takes the form

$$L = 4\pi cGM(1-\beta)/k_0. \tag{7}$$

This appears to make the luminosity depend on the *boundary* value of the opacity, which is at first sight a still more surprising conclusion than that for our original model, $k = \text{const.}$, $\epsilon = \text{const.}$

Eddington did not, however, proceed in this way. From his study of the standard model with $k = \text{const.}$, $\epsilon = \text{const.}$, he had determined a numerical value of k, which, since k had been assumed constant throughout the interior, might be supposed to provide a *mean value* for the interior. He was reluctant to transfer the numerical value he had previously assigned to the *interior* of the model $k = \text{const.}$, $\epsilon = \text{const.}$, to the *boundary* of the more general model $k\eta = \text{const.}$, and he evaded the crucial inference that the constant value of $k\eta$ is its boundary value. He was under the impression that the fundamental equation (3) did not hold good at the boundary. Actually it holds good to the same extent as the formula

$$T^4 = \tfrac{1}{2}T_1^4(1 + \tfrac{3}{2}\tau)$$

holds good for the temperature distribution near the boundary. For differentiating, since $d\tau = -k\rho dr$, we get

$$\frac{dT^4}{dr} = -\tfrac{3}{4}T_1^4 k\rho,$$

or, since the effective temperature T_1 is defined by

$$(4\pi r_0^2)(\tfrac{1}{4}acT_1^4) = L,$$

we get

$$\frac{d(\frac{1}{3}aT^4)}{dr} = -\frac{kL}{4\pi r_0^2 c}\rho, \tag{8}$$

which is just (3), applied at the boundary. Eddington always insisted that his analysis was inapplicable to the boundary. He wrote (*I.C.S.*, p. 101): "The equation breaks down under the same circumstances as the corresponding equation for a material fluid, viz. when the flow is so rapid that the pressure-gradient can no longer be calculated hydrostatically. This happens near the surface of a star. The argument cannot apply to any part of the star which we can *see*; for the fact that we see it shows that its radiation is not 'enclosed'. But at a small depth below the photosphere, the equation becomes a tolerable approximation".

Actually this process of obtaining a differential equation for the flow of radiation, applying it near the boundary and then integrating it, is quite unnecessary. As I shall show later, we can obtain an accurate form of the luminosity formula from the formula $T^4 = \frac{1}{2}T_1^4(1 + \frac{3}{2}\tau)$ as it stands.

I believe Eddington was profoundly mistaken in declining to face the fact that if k is not constant throughout the star, but $k\eta$ is constant, then the value of k occurring in the luminosity formula is the boundary value of k. With a slight modification, we shall see later that the same result holds good without any restriction on $k\eta$. The reason that the boundary value, and not any internal value, occurs in the luminosity formula, is that the luminosity formula just tells us the rate of radiation of the outer parts of the star to space, and has nothing to do in itself with internal equilibrium; the star simply *shines* at the rate L. So far from the arguments not applying to any part of the star which we can see, it is precisely the part of the star which we can see which gives rise to the formula.

This state of affairs is worth considering in detail. To my mind it leads to an entirely different view of the whole subject of stellar equilibrium. Eddington's view was that the radiant energy liberated in the interior forces its way out, when the star is in a steady state, under the gradient of its own density. But this gradient is only maintained by the leakage of energy at the surface. The mechanism by which the gradient, and so the steady state, is set up is just the escape of radiation at the surface. Were the star sealed off by an adiabatic wall at its surface, no steady state of flow could be set up—we should just have an isothermal chamber.

Now the equation expressing the flow of energy, as used by Eddington and as quoted above, is precisely the same equation as would be written down if the star were a freely cooling body, radiating to space. At any one instant, the star is radiating to space from its surface layers, and interchanging energy amongst its interior elements, in a way depending solely on its opacity and its temperature distribution, independent of what energy-sources are present. If energy-sources are not present, in a short interval of time δt the temperature T changes at each point to some value $T-\delta T$; if energy-sources are present, the temperature changes at each point to some other value, perhaps $T+\Delta T$; if the energy-generation is such that the state is steady, the temperature T remains constant at each point, the energy-generation just restoring the loss of temperature due to radiating. But in all three cases, the rate of radiation to space, at the instant considered, is the same. And, as remarked, this rate of radiation to space depends only on the temperature distribution and opacity. It is true that in the long run the distribution of energy-sources influences the temperature distribution. But what we need to know momentarily is the temperature distribution—and opacity. Clearly it is only the temperature distribution and opacity in the outermost layers—as far, in fact, as the depth to which we see—which are relevant to the radiation to space. This is the fundamental reason why it is the boundary value of the opacity which occurs in the luminosity formula.

When k is assumed constant throughout the interior, as in the first form of the standard model, it is immaterial to which point in the star it is supposed to refer; and accordingly Eddington naturally considered that the numerical value determined for k from the mass, luminosity and molecular weight referred to the deep interior. When we make the less restrictive assumption $k\eta=\text{const.}$, we find that the place in the star to which the astronomically determined value relates is the *boundary*. But Eddington was still under the impression that he was evaluating the interior opacity. He fought shy of the plain straightforward mathematical procedure of evaluating the product $k\eta$ by noting that at the boundary $\eta=1$. The interior opacity was his darling, and he flinched at sacrificing it on a mathematical altar. I think this was not a case of Homer nodding, but of Homer being human.

It may be objected that no one supposes $k\eta$ to remain exactly constant right up to the boundary, in an actual star. I will deal with this objection in a moment. I want to emphasize first that we must not confuse an actual star with a model. What we are doing is to ascertain the properties of the model. If the proposed model satisfies $k\eta=\text{const.}$, then the value of the opacity determined by the mass and luminosity is the

boundary value. If, on the other hand, $k\eta$ is not constant, then β is not constant throughout the star, and the luminosity formula and quartic equation both need reconsideration. To this case we now apply ourselves.

When $k(r)L(r)/M(r)$ is not constant, *i.e.* when the flux of energy is not proportional to gravity g, equation (4) above cannot be conveniently integrated. But we do not need to integrate it to obtain a formula for the luminosity. All we need to do is to take its limit as r tends to its boundary value. Writing p' for the radiation pressure, P for the total pressure $p+p'$, the equation is

$$\frac{dp'}{dP}=\frac{k(r)L(r)}{4\pi cGM(r)}.$$

At the boundary, $L(r)\rightarrow L$, $M(r)\rightarrow M$, and since p' and P are both small at the boundary, the limit of dp'/dP is effectively the limit of p'/P (apart from an extra-photospheric complication), and this limit is by definition $1-\beta_0$, where the suffix o refers to the boundary. Hence we get

$$L=4\pi cGM(1-\beta_0)/k_0. \tag{9}$$

The problem thus reduces itself to the determination of β_0, the boundary value of β. We may put the question thus: when β is not a constant, does the quartic equation fix a mean value of β through the star, or does it determine β at some particular point in the star, and if so, what point? The answer is that the quartic equation, properly re-derived to suit these new circumstances, determines the *boundary* value of β, which is just what we need.

When β is not constant, the interior is no longer an Emden polytrope of index $n=3$, and the steps by which the quartic equation was originally derived appear no longer valid. It was this question, of the solution when β is variable, to which I addressed myself in my paper of 1929 November on "The Masses, Luminosities and Effective Temperatures of the Stars" *, a paper which was so drastically criticised by Eddington soon afterwards.† There is no doubt that somehow or other Eddington was intensely irritated by my paper. He attempted to dispose of it by reversing some of its mathematics, a procedure for which he had years earlier rebuked Sir James Jeans.‡ The real point of my paper was somewhat lost sight of in the subsequent controversy§: it was that the procedure originally used by Eddington to derive a quartic equation for β when β is constant can readily be modified to derive a quartic equation for β when β is *not* constant. This quartic equation contains, as before, the square of the stellar mass, M^2 and the fourth power of the molecular weight, now the *boundary* molecular weight, μ_0^4; the constant of proportionality between $1-\beta$ and $\beta^4M^2\mu_0^4$ is again the boundary value of the solution of a differential equation; lastly, the solution β of this quartic equation is precisely the value β_0 demanded by relation (9). I give a brief demonstration in the Appendix.

It follows that the generalisation of Eddington's analysis to the case where β is not a constant leads to the evaluation, through (9) above, of k_0, the boundary opacity. Actually the analysis given in the Appendix is more general still than for the conditions assumed in the standard model. For it has not been found necessary to assume that the star is gaseous, save in its outer layers; and the equation of radiative equilibrium is not invoked, save in the outer layers.

The constant of proportionality in the more general quartic equation turns on the solution of

$$\frac{1}{x^2}\frac{d}{dx}\left(\frac{x^2}{y}\frac{dz}{dx}\right)=-y, \tag{10}$$

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* *M.N.*, 90, 17, 1929. † *M.N.*, 90, 284, 1930. ‡ *M.N.*, 78, 113, 1917. § *M.N.*, 90, 678, 1930.

with z some function of y, or on the solution, more explicitly, of

$$\frac{1}{x^2}\frac{d}{dx}\left[\frac{x^2}{\theta^3}\frac{d}{dx}(\theta^4\phi(\theta))\right] = -\theta^3. \qquad (10')$$

By considering numerical solutions of these generalisations of Emden's equation, it would be possible to evaluate k_0 numerically. I, indeed, attempted the latter indirectly in the paper cited. But I am concerned here with the natural philosophy underlying the situation.

That the boundary opacity is involved we have already seen to be a consequence of the fact that the portion of the star we actually see is the outer part, shining into space. Our new analysis confirms this, but it makes the situation clearer. For the derivation of the luminosity formula and quartic equation involve only the gaseous character and opacity of the outer layers, radiative equilibrium in these outer layers and the mechanical equilibrium of the star as a whole in its actual state of compressibility. The latter is the nexus between the interior and the exterior; it amounts to the condition that the boundary layers are just floating on the whole mass.

These conclusions differ so conspicuously from Eddington's own interpretation of his analysis, and indeed from the generally current treatments of the subject, that I give an independent, more rigorous analysis below. There we shall see that the condition of *floating* of the photospheric or boundary gases actually provides the quartic equation immediately; and that the phrase *boundary opacity*, when examined in detail, means the mean value of the opacity reckoned from the actual boundary inwards to a level just beneath the photosphere. There is no immediate dependence in any way on interior opacity; the only influence of the interior opacity is an indirect one, in modifying the compressibility of the interior.

But I want first to show you directly how hopeless is the quest for a direct determination of interior opacity from the very situation itself. The opacity occurs in the equations only in the form of a product with the integrated energy generation $L(r)$, namely as $k(r)L(r)$. The value of $L(r)$ is known at only one point, viz. the boundary, where its value is L. $L(r)$ may be expected to decrease as r decreases, but otherwise, its behaviour is not known. (I am considering, in this address, what can be deduced from *equilibrium* considerations only, as Eddington did, without making assumptions about energy generation.) We can assign to the opacity any value we please, at any r, by adjusting $L(r)$, without interfering with the internal equilibrium.* In particular we can make the opacity in the vicinity of the centre what we will by a suitable adjustment of the behaviour of $L(r)$ for r small. The fact is, the *central opacity* is the wrong measure of the quantity astronomically determined. The luminosity $L(r)$ can be separated from $k(r)$ only at the boundary, where $L(r)=L$, $k(r)=k_0$.

The point is fundamentally important, because it is through the supposed determination of the opacity in the interior of a star that the chemical constitution of the interiors of stars has been inferred, and I wish seriously to criticise the grounds of this inference. I consider that I have shown that the immediate inference from an assumed relative density-distribution in a stellar interior is the value of the opacity, and hence the mean molecular weight, near the boundary. The evidence is compatible with the outer layers being predominantly hydrogen. The inference as to the chemical composition of the interior is an extrapolation. It may be a highly plausible one, but it is not a legitimate deduction from the theory of stellar equilibrium.

Because this conclusion is revolutionary, an independent mode of derivation is desirable. I have substantially given the analysis which follows in earlier papers in the *Monthly Notices* †, but I have recently re-arranged the analysis to exhibit the results

* E. A. Milne, "Über die Frage der Opazität der Sternmaterie", *Zeits. für Astrophys.*, 3, 253, 1931.

† *M.N.*, 97, 57, 1937; 98, 21, 1937.

more clearly. The analysis is given in detail in the Appendix. Here I trace its general features.

I begin where I began twenty-four years ago with my first paper * read before this Society: I begin with the equation for the temperature distribution in the outer layers of a star in terms of optical depth τ,

$$B(\tau)=\tfrac{1}{2}F(1+\tfrac{3}{2}\tau),$$

where πF is the net outward flux† of energy, $B(\tau)$ the intensity of black-body radiation at optical depth τ. Since $B=(\sigma/\pi)T^4$, where T is the absolute temperature, and since $\pi F=\sigma T_1^4$, where T_1 is the *effective* temperature of the star, this reduces to the form already quoted

$$T^4=\tfrac{1}{2}T_1^4(1+\tfrac{3}{2}\tau). \tag{11}$$

Here

$$d\tau=-k\rho dr.$$

The force due to radiation pressure on unit area of thickness dr is

$$\frac{L}{4\pi r_0^2}\frac{k\rho dr}{c},$$

and the equation of mechanical equilibrium is accordingly

$$\frac{dp}{dr}=-g\rho+\frac{kL}{4\pi r_0^2 c}\rho. \tag{12}$$

Here r_0 is the stellar radius, and

$$g=GM/r_0^2, \qquad (4\pi r_0^2)(\tfrac{1}{4}acT_1^4)=L. \tag{13}$$

Substituting for r_0^2, we get from (12) and (13)

$$\frac{dp}{dr}=-\frac{\pi cGMaT_1^4}{L}\rho+\tfrac{1}{4}aT_1^4k\rho.$$

Integrating inwards to optical depth τ we get

$$p(r)=\tfrac{1}{4}aT_1^4\left[\frac{4\pi cGM}{L}\int_0^\tau\frac{d\tau}{k}-\tau\right].$$

But from (11),

$$\tau=\frac{4}{3}\frac{T^4-\tfrac{1}{2}T_1^4}{T_1^4}. \tag{14}$$

Hence

$$p(r)=\tfrac{1}{3}a(T^4-\tfrac{1}{2}T_1^4)\left[\frac{4\pi cGM}{L}\frac{1}{\tau}\int_0^\tau\frac{d\tau}{k}-1\right].$$

But

$$\frac{1}{\tau}\int_0^\tau\frac{d\tau}{k}=\int\rho dr\Big/\int k\rho dr=\frac{1}{\bar{k}}, \tag{15}$$

where $\bar{k}$ denotes the mean value of the absorption coefficient averaged over the mass *exterior* to the depth r considered. Thus

$$p(r)=\tfrac{1}{3}a(T^4-\tfrac{1}{2}T_1^4)\left[\frac{4\pi cGM}{\bar{k}L}-1\right]. \tag{16}$$

It is particularly to be noted that we have used the condition of radiative equilibrium in its integrated form (11) and that we have not needed to differentiate it; (11) is the

* *M.N.*, 81, 361, 1921.

† The formula is a more accurate form of a formula given in the pioneer work of Schwarzschild, *Gött. Nach.*, 1906, p. 41.

approximate solution of the integral equation for radiative equilibrium which preserves the proper net flux. Relation (16) has been derived by considering only the portions of the star *exterior* to the level r in question.

We now have to express that these outer layers are *floating* in equilibrium on a compressible interior. The most direct way of doing this is to calculate the actual gas-pressure $p(r)$ at this same point r by working *outwards* from the stellar centre. We do this quite generally, not making any special assumptions about the deep interior; we leave its compressibility entirely arbitrary, and we do not need to consider the flow of energy, or, until we actually reach the level r, the equation of state. At this sub-photospheric level we may fairly assume the material to be gaseous, of molecular weight μ. In the notation I adopt, we find thus

$$p(r)=\frac{(R/\mu)^4T^4}{4\pi G^3\beta^3[M(r)]^2}\frac{y^2}{z^3}\left[-x^2\frac{dz}{dx}\right]^2, \tag{17}$$

where y and z measure the density and pressure in reduced units; y and z are connected with x by equation (10) above, the function $z\equiv z(y)$ expressing the compressibility, and x measuring the reduced radius. For any arbitrary function $z\equiv z(y)$, the differential equation (10) above is supposed to be solved with the central conditions

$$\text{at } x=0,\quad y=1,\quad z=1,\quad \frac{dy}{dx}=0,$$

as for Emden's equation, and the solution is to be continued outwards to near the boundary, *i.e.* the first zero of y. This solution provides the numerical value of

$$\frac{y^2}{z^3}\left[-x^2\frac{dz}{dx}\right]^2 \tag{18}$$

at any point. The value of this expression depends on the complete march of $z=z(y)$ from $x=0$ to the level considered.

The factor T^4 in (17) has nothing to do with radiation pressure. The fraction β in (17) is a variable. The definition of β is given by

$$\frac{p(r)}{\frac{1}{3}aT^4}=\frac{\beta}{1-\beta}. \tag{19}$$

The value $p(r)$, obtained by outward integration, given by (17), must equal the value of $p(r)$, obtained by inward integration, given by (16). The equality of the two will express that the gaseous outer layer in question is just floating on the interior.

Strictly speaking, we should equate (16) and (17) and eliminate β at the same time by (19); for we have just three relations between which we can in theory eliminate p and β. But it is more convenient, and closer to Eddington's original procedure, to retain β as a parameter. From (16) and (19) we get, eliminating p,

$$\frac{\beta}{1-\beta}=\left(1-\frac{\frac{1}{2}T_1^4}{T^4}\right)\left(\frac{4\pi cGM}{\bar{k}L}-1\right), \tag{20}$$

and from (17) and (19), again eliminating p, we get

$$\frac{\beta^4}{1-\beta}=\frac{(R/\mu)^4}{4\pi G^3(\frac{1}{3}a)[M(r)]^2}\frac{y^2}{z^3}\left[-x^2\frac{dz}{dx}\right]^2. \tag{21}$$

When, using (20), we descend a little way into the sub-photospheric layers, T^4 rapidly increases. We can therefore neglect the term $\frac{1}{2}T_1^4/T^4$ in comparison with unity (this is

the equivalent of Eddington's procedure of neglecting a small constant of integration). The result is that a little way inside the photosphere, β takes the value β_0, given by

$$\frac{\beta_0}{1-\beta_0} = \frac{4\pi cGM}{\bar{k}L} - 1,$$

or

$$L = 4\pi cGM(1-\beta_0)/\bar{k}. \tag{22}$$

Here $\bar{k}$ is the mean opacity of the layer *exterior* to the level to which β_0 refers.

Equation (21) determines β at any level in terms of an outward integration from the centre. To obtain the value β_0 required in (22), we put $M(r) = M$, $\mu = \mu_0$ (the sub-photospheric molecular weight), and carry through the integration to $x = x_0$, the position of the first zero of y. The equation for β_0 is then

$$\frac{\beta_0^4}{1-\beta_0} = \frac{(R/\mu_0)^4}{4\pi G^3(\frac{1}{3}a)M^2}\left(\frac{y^4}{z^3}\right)_0\left[-\frac{x^2}{y}\frac{dy}{dx}\right]_0^2. \tag{23}$$

The suffix o denotes evaluation at $x = x_0$. Our problem is now solved.

We first verify that the solution reduces to Eddington's solution when the interior is such that the density-distribution is that of an Emden polytrope $n = 3$. In this case,

$$y = \theta^3, \qquad z = \theta^4, \qquad x = (3+1)^{\frac{1}{2}}\xi,$$

and the purely numerical factors in (23) reduce to

$$\left[-\frac{x^2}{\theta^3}\frac{d\theta^4}{dx}\right]_{x=x_0}^2 = 64\left(-\xi^2\frac{d\theta}{d\xi}\right)_0^2,$$

and so the quartic equation reduces to Eddington's form as given in (14) of the Appendix below.

Thus by the present method, of expressing that the outer layers of the star are floating in equilibrium, we recover Eddington's formulæ, with this difference: (*a*) that we have not assumed radiative equilibrium in the interior; (*b*) that we have assumed the gas-laws only in the outer layers; (*c*) that the value of the opacity concerned in the luminosity formula is the mean outer opacity, not the interior opacity. To assume that the compressibility of the interior is that of a polytrope $n = 3$, though compatible with radiative equilibrium and obedience to the gas-laws in the interior, is clearly a much weaker assumption than these latter assumptions.

Again, if more generally we describe the compressibility of the interior as given by the relations

$$y = \theta^3, \qquad z = \theta^4\phi(\theta),$$

we also get a differential equation for θ, of a type which is a generalisation of Emden's; we can integrate it by quadratures for any assigned $\phi(\theta)$; and we finally evaluate the purely numerical factor in the quartic equation as

$$\frac{y^4}{z^3}\left(-\frac{x^2}{y}\frac{dz}{dx}\right)^2 = \lim_{\theta\to 0}\frac{1}{[\phi(\theta)]^3}\left[-\frac{x^2}{\theta^3}\frac{d}{dx}(\theta^4\phi(\theta))\right]^2 = \frac{16}{\phi(0)}\left[-x^2\frac{d\theta}{dx}\right]_{x=x_0}^2. \tag{24}$$

As before, this numerical factor depends on the complete march of $\phi(\theta)$ between centre and boundary. The factor *recapitulates*, in a phrase I have used before, the complete structure of the star between centre and boundary.

When I obtained similar results in 1929 and 1930, Eddington was under the impression that my results were purely *photospheric* relations. It is true that the whole situation arises from the equality of two different calculations of the pressure in the immediate sub-photospheric region. But I think that it escaped him that the essential

numerical coefficient, which, in his own case, he quoted from Emden's tables and was thus derived from a complete quadrature, was also in my more general case derived by a complete quadrature from centre to surface.

Consider a cubic centimetre of gas situated some little distance below the photosphere. Suppose we could extract it, at its actual temperature and pressure—siphon it off as it were—and examine it in a laboratory. What could we learn from it?

First of all, its pressure and temperature tell us something about its depth below the surface. This information is what is conveyed by the luminosity formula. Secondly, its pressure and temperature tell us something about the degree of compressibility of the whole interior. This information is what is conveyed by the quartic equation. The numerical value of

$$\left[\frac{y^4}{z^3}\left(-\frac{x^2}{y}\frac{dy}{dx}\right)^2\right]_{x=x_0}$$

may be considered the *signature* of the interior on the element of gas concerned. Each journey we take in imagination, one from the boundary inwards to a sub-photospheric level, one from the centre outwards to the same sub-photospheric level—each journey is accompanied with certain thermodynamic experiences: the luminosity formula records the one, the quartic equation the other. The specimen of gas we have imagined as available to us bears the imprint of both journeys. It follows that we can use the equality of the two ways of calculating the pressure to obtain some information about the compressibility of the interior.

The group of formulæ here considered connect the luminosity, exterior opacity, exterior molecular weight, total mass and interior compressibility. Somehow these must find a mutual adjustment. When we observe a star in a steady state, this adjustment has been carried out. Pure equilibrium theory does not tell us how, but presumably it is done by adjustment of the radius.

This is not the occasion to go into numerical detalls: I am concerned here only with principles. Given a star of observed luminosity and observed spectrum, we can determine the chemical composition and mean molecular weight, and so the mean exterior opacity. Substituting L, M and $\bar{k}$ in the luminosity formula, we can determine the value of β_0. Inserting this in the quartic equation, we can evaluate the numerical coefficient present in that equation. This must then be compared with various values of the same numerical coefficient calculated for different compressibilities by outward integration from the centre. For example we could conduct quadratures for various values of a parameter λ defining compressibility functions $\phi(\theta)$ of the form

$$\phi(\theta) \equiv 1 + \lambda(1 - \theta).$$

Thus $\lambda = 0$ would correspond to a polytrope $n = 3$. For $\lambda > 0$, the total pressure would decrease towards the boundary *less* rapidly at first than for the polytrope $n = 3$. Comparison of the astronomical and theoretical values of (24) would yield a numerical value of λ, the actual value realised for the star in question. This would indicate the interior compressibility.

We see that we are not in a position legitimately to draw conclusions about the opacity or molecular weight of the deep interior, or about the mode of transfer of energy there, or indeed, whether it be gaseous or not. But we *do* make eventually a conclusion about the interior, namely about its general compressibility. I think that this is the utmost that is capable of being directly inferred from observations of the masses, luminosities and effective temperatures of the stars.

To summarise: I yield to no one in my admiration for the broad incisive sweep, the tremendous drive, the physical setting, of Eddington's researches on stellar structure. But in the most important deduction that he made therefrom, I think he misled himself. His luminosity formula gives the outer opacity, not the interior opacity. The structure

of the interior manifests itself only by its *signature* on these outer layers; its general compressibility affects the ratio of radiation-pressure to total pressure in the sub-photospheric layers. The final picture of a star may or may not turn out to be something not widely different from Eddington's picture, but I think it is of primary importance to have the logical relationships clear and unassailable. That is the main contribution which a mathematician can make to the natural philosophy of stellar structure.

MATHEMATICAL APPENDIX

1. *Derivation of the Formulæ for the Standard Model.*—Let p be the gas-pressure, p' the radiation pressure, ρ the density, T the temperature, at a point distant r from the centre of an equilibrium configuration. Let $M(r)$ be the mass enclosed within radius r, $L(r)$ the total generation of energy within radius r. Then the equation of mechanical equilibrium was shown by Eddington to take the expected form

$$\frac{dp}{dr}+\frac{dp'}{dr}=-\frac{GM(r)}{r^2}\rho, \tag{1}$$

where the second term on the left-hand side expresses the mechanical effect of radiation-pressure; and the equation of transfer of radiant energy was shown by Eddington to take the form

$$\frac{dp'}{dr}=-\frac{k\rho}{c}\frac{L(r)}{4\pi r^2}. \tag{2}$$

Putting

$$p+p'=P, \tag{3}$$

and dividing, we get

$$\frac{dp'}{dP}=\frac{k}{4\pi cG}\frac{L(r)}{M(r)}. \tag{4}$$

In that form of the standard model in which the generation of energy is uniform throughout the mass, $L(r)$ is proportional to $M(r)$, and so

$$L(r)/M(r)=L/M, \tag{5}$$

where L is the total bolometric luminosity, and M is the total mass. If then k is a constant, the same throughout the interior, equation (4) can be integrated, and neglecting a small constant of integration, we get

$$p'=\frac{kL}{4\pi cGM}P. \tag{6}$$

Thus the ratio of radiation-pressure to total pressure is constant throughout the configuration. Calling this ratio $(1-\beta)$, we get

$$L=4\pi cGM(1-\beta)/k. \tag{7}$$

The problem of ascertaining the luminosity therefore turns on the determination of β. In Eddington's first paper * in the *Monthly Notices* on this subject, the determination of β is rather obscure. In his second paper † in the *Monthly Notices* he obtained his famous quartic equation by quoting results from Emden's *Gaskugeln*. In his *Astrophysical Journal* paper of 1918 November ‡ he used a dimensional argument. In the *Internal Constitution of the Stars* he derived the quartic equation from general formulæ applicable to polytropes of any order n, by taking the particular case $n=3$. As it is with the meaning of the quartic equation that we shall be mostly concerned, I give the simple direct derivation which is missing in Eddington's published works.

* *M.N.*, 77, 16, 1916. † *M.N.*, 77, 596, 1917. ‡ *Ap. J.*, 48, 205, 1918.

Assuming the material to be an ideal gas of molecular weight μ, we have for its equation of state

$$p=(R/\mu)\rho T.$$

Hence

$$\frac{\beta}{1-\beta}=\frac{p}{p'}=\frac{(R/\mu)\rho T}{\frac{1}{3}aT^4}=\frac{R/\mu}{\frac{1}{3}a}\frac{\rho}{T^3}. \tag{8}$$

Since in this model β is constant, ρ/T^3 is constant through the star. The equation of mechanical equilibrium can now be written in the form

$$\frac{d}{dr}\left(\frac{\frac{1}{3}aT^4}{1-\beta}\right)=-\frac{GM(r)}{r^2}\frac{\beta}{1-\beta}\frac{\frac{1}{3}a}{R/\mu}T^3.$$

But

$$\frac{dM(r)}{dr}=4\pi r^2\rho. \tag{9}$$

Hence

$$\frac{1}{r^2}\frac{d}{dr}\left[\frac{r^2}{T^3}\frac{dT^4}{dr}\right]=-\frac{4\pi\beta G}{R/\mu}\rho=-\frac{4\pi G(\frac{1}{3}a)}{(R/\mu)^2}\frac{\beta^2}{1-\beta}T^3.$$

Put

$$T=T_c\theta, \tag{10}$$

where T_c is the central temperature; and then put

$$r=\frac{R/\mu}{\beta T_c}\left[\frac{1-\beta}{\pi G(\frac{1}{3}a)}\right]^{\frac{1}{2}}\xi. \tag{11}$$

Then the differential equation for T reduces to

$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\theta}{d\xi}\right)=-\theta^3, \tag{12}$$

which is Emden's differential equation for a polytrope $n=3$. This determines the march of θ with ξ from centre to boundary. Since the configuration is assumed gaseous throughout, the solution to be selected is that for which

$$\text{at } \xi=0, \qquad \theta=1, \qquad \text{and} \qquad \frac{d\theta}{d\xi}=0. \tag{13}$$

It remains to determine the total mass of the configuration—that is, the mass enclosed between $\theta=1$ and $\theta=0$. Let ξ_0 be the value of ξ for which θ first vanishes. Then

$$M=\int_0^{r_0}4\pi\rho r^2dr=4\pi\left(\frac{\beta}{1-\beta}\frac{\frac{1}{3}a}{R/\mu}T_c^3\right)\frac{(R\mu/)^3}{\beta^3T_c^3}\left[\frac{1-\beta}{\pi G(\frac{1}{3}a)}\right]^{\frac{3}{2}}\int_0^{\xi_0}\theta^3\xi^2d\xi,$$

$$=\frac{4\pi}{(\pi G)^{\frac{3}{2}}(\frac{1}{3}a)^{\frac{1}{2}}}\frac{(1-\beta)^{\frac{1}{2}}}{\beta^2}\left(\frac{R}{\mu}\right)^2\int_0^{\xi_0}\theta^3\xi^2d\xi.$$

From the differential equation (12),

$$\int_0^{\xi_0}\theta^3\xi^2d\xi=\left[-\xi^2\frac{d\theta}{d\xi}\right]_{\xi=0}^{\xi_0}=-\xi_0^2\left(\frac{d\theta}{d\xi}\right)_{\xi=\xi_0}.$$

Thus

$$1-\beta=\beta^4\mu^4M^2\frac{\pi G^3(\frac{1}{3}a)}{16R^4}\Big/\left[-\xi_0^2\left(\frac{d\theta}{d\xi}\right)_0\right]^2. \tag{14}$$

This is the famous quartic equation for β. The numerical value of $[-\xi_0^2(d\theta/d\xi)_0]^{-2}$ is the boundary value of an argument tabulated by Emden.

2. The analysis of the above paragraph holds good as it stands if k and $L(r)/M(r)$ vary in any way subject to the condition

$$k(r)\,L(r)/M(r) = \text{const.} \tag{15}$$

The value of this constant is $k_0 L/M$, where k_0 is the boundary value of the opacity. Equation (6) becomes

$$p' = \frac{k_0}{4\pi cG}\frac{L}{M}P,$$

and putting $p'/P = 1-\beta$ as before, (7) becomes

$$L = 4\pi cGM(1-\beta)/k_0, \tag{16}$$

where β is given by the same quartic equation (14).

3. *Case of β not Constant.*—Now suppose that β is no longer constant through the star. In the equation of mechanical equilibrium

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2}\rho,$$

put

$$P = P_c z, \qquad \rho = \rho_c y, \qquad r = \left(\frac{P_c}{4\pi G\rho_c{}^2}\right)^{\frac{1}{2}} x. \tag{17}$$

Then it becomes after a further differentiation

$$\frac{1}{x^2}\frac{d}{dx}\left[\frac{x^2}{y}\frac{dz}{dx}\right] = -y. \tag{18}$$

When $y=\theta^n$, $z=\theta^{n+1}$, this reduces to Emden's equation of order n on putting

$$x = (n+1)^{\frac{1}{2}}\xi. \tag{19}$$

For any given compressibility of the stellar material, z will be some function of y. Whatever relation between y and z is imposed, let (18) be solved numerically just as Emden's equation is solved numerically, with the central conditions:

$$\text{at } x=0, \qquad y=1, \qquad z=1, \qquad dy/dx=0;$$

and let the solution be continued until y vanishes. Let this first zero occur at $x=x_0$. To the order of approximation here relevant, z will also vanish at this point.

The total mass M is now given by

$$M = \int_0^{r_0} 4\pi\rho r^2 dr = 4\pi\left(\frac{P_c}{4\pi G\rho_c{}^2}\right)^{\frac{3}{2}}\rho_c\int_0^{x_0} yx^2dx = \frac{P_c{}^{\frac{3}{2}}}{(4\pi)^{\frac{1}{2}}G^{\frac{3}{2}}\rho_c{}^2}\left[-\frac{x^2}{y}\frac{dz}{dx}\right]_{x=x_0}. \tag{20}$$

The value of $\left(-\frac{x^2}{y}\frac{dz}{dx}\right)_0$ is to be found by quadrature of the equation (18). Its value clearly depends on the whole march of the function $z=z(y)$ from centre to boundary.

Now suppose that the *outer* layers of the star are gaseous, of molecular weight μ_0. We make no supposition about the interior. Then in these outer layers

$$p' = (1-\beta)P = \tfrac{1}{3}aT^4,$$
$$p = \beta P = (R/\mu_0)\rho T.$$

Eliminating T and substituting from (17) for P and ρ, we get

$$\frac{1-\beta}{\beta^4} = \frac{\frac{1}{3}a}{(R/\mu_0)^4}\frac{P_c{}^3}{\rho_c{}^4}\frac{z^3}{y^4}. \tag{21}$$

When the configuration was an Emden polytrope of order $n=3$, we had $y=\theta^3$, $z=\theta^4$. Since we are in essence considering configurations akin to Emden polytropes, we may put parametrically

$$y=\theta^3, \qquad z=\theta^4\phi(\theta), \tag{22}$$

where $\phi=1$ at $\theta=1$ and $\phi(\theta)$ tends to a definite limit $\phi(0)$ as $\theta\to 0$. Otherwise ϕ may behave in any manner. Squaring equation (20) and substituting for P_c^3/ρ_c^4 from (21) we get

$$M^2=\frac{(R/\mu_0)^4}{4\pi G^3(\frac{1}{3}a)}\,\frac{1-\beta}{\beta^4}\,\frac{y^4}{z^3}\left[-\frac{x^2}{y}\frac{dy}{dx}\right]_0^2. \tag{23}$$

We are anxious to obtain the value of $1-\beta_0$, where β_0 is the value of β at the boundary. Relation (21) shows that the ratio

$$\frac{1-\beta}{\beta^4}\,\frac{y^4}{z^3}$$

is finite at any place where the star is gaseous, and the numerical value of this is determined by (23). The variables y and z vanish at the boundary, but

$$\lim_{x\to x_0}(z^3/y^4)=[\phi(0)]^3,$$

whilst

$$\left[-\frac{x^2}{y}\frac{dz}{dx}\right]_0^2=\lim_{x\to x_0}\left[-\frac{x^2}{\theta^3}\frac{d}{dx}(\theta^4\phi(\theta))\right]^2=[\phi(0)]^2\left[-4x^2\frac{d\theta}{dx}\right]_0^2.$$

Hence (23) gives

$$M^2=\frac{(R/\mu_0)^4}{4\pi G^3(\frac{1}{3}a)}\,\frac{1-\beta_0}{\beta_0^4}\,\frac{1}{\phi(0)}\left[-4x^2\frac{d\theta}{dx}\right]_0^2. \tag{24}$$

This is the form of the quartic equation for β_0 when β is not constant, necessarily, throughout the star. It includes (14) as a particular case, to which it reduces for

$$\phi(\theta)\equiv 1, \qquad n=3, \qquad x=(3+1)^{\frac{1}{2}}\xi.$$

4. *Calculation of Gas-Pressure in a sub-photospheric layer by outward integration from the Centre of the Star.*—In equation (20) above (section 3) substitute for P_c and ρ_c their values

$$P_c=P/z, \qquad \rho_c=\rho/y$$

and then substitute, for a layer known to be gaseous,

$$\rho=p/(R/\mu)T$$

and set

$$P=p/\beta.$$

We get

$$M(r)=\frac{P_c^{\frac{3}{2}}}{(4\pi)^{\frac{1}{2}}G^{\frac{3}{2}}\rho_c^2}\left[-\frac{x^2}{y}\frac{dz}{dx}\right]=\frac{P^{\frac{3}{2}}}{(4\pi)^{\frac{1}{2}}G^{\frac{3}{2}}\rho^2}\,\frac{y^2}{z^{\frac{3}{2}}}\left[-\frac{x^2}{y}\frac{dz}{dx}\right]$$

$$=\frac{(R/\mu)^2T^2}{(4\pi)^{\frac{1}{2}}G^{\frac{3}{2}}p^{\frac{1}{2}}\beta^{\frac{3}{2}}}\,\frac{y^2}{z^{\frac{3}{2}}}\left[-\frac{x^2}{y}\frac{dz}{dx}\right].$$

Squaring we get

$$p(r)=\frac{(R/\mu)^4T^4}{4\pi G^3[M(r)]^2\beta^3}\,\frac{y^4}{z^3}\left[-\frac{x^2}{y}\frac{dz}{dx}\right]^2. \tag{25}$$

In this the numerical factor

$$\frac{y^4}{z^3}\left[-\frac{x^2}{y}\frac{dz}{dx}\right]^2$$

is to be evaluated by integration of the differential equation (18) outwards from the centre, with z any definite function of y subject to $z=1$ for $y=1$, and with the central conditions:

$$\text{at } x=0, \qquad y=1, \qquad dy/dx=0.$$

As before, z and y may be supposed to vanish at the boundary, say where $x=x_0$. Here $M(r)=M$, effectively, and the value of p at the level at which the temperature is T is given by

$$p=\frac{(R/\mu)^4T^4}{4\pi G^3M^2\beta^3}\lim_{x\to x_0}\frac{y^4}{z^3}\left[-\frac{x^2}{y}\frac{dz}{dx}\right]^2. \tag{26}$$

This is the equation referred to in the text of the address. The occurrence of the factor T^4 in p has nothing to do, it may be remarked, with the T^4 occurring in the formula $\frac{1}{3}aT^4$ for radiation pressure, which in this section we have not used.

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